THESIS FOR THE DEGREE OF DOCTOR OF TECHNOLOGY

Quantifying Levels of Automation

- to enable competitive assembly systems

ÅSA FASTH

Department of Product and production Development
CHALMERS UNIVERSITY OF TECHNOLOGY
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- to enable competitive assembly systems

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ABSTRACT

Production companies frequently have to meet demands and requirements, both internal and external, which trigger a plan for change in different production areas. Assembly systems of today are heading towards more customised production, i.e. smaller batches, shorter cycle times and increased number of variants. As a result, companies have to find more flexible methods for assembling their products and become more proactive in the assembly system itself. Identifying new strategies becomes vital and can be achieved by designing the assembly system in a structured way with the most advantageous cognitive and mechanical Level of Automation.

The aim of this thesis is to show that by quantifying, measuring and analysing physical and cognitive Levels of Automation it is possible to enable competitive assembly systems.

'*If it is not Quantifiable it is not true'* – this is a common statement among engineers who rather use numbers than words when describing a phenomenon. This thesis will discuss the phenomenon of Levels of Automation from both a quantitative and qualitative point of view. Furthermore it will discuss whether it is necessary to have more than one level or dimension of automation and if so, what benefits this creates for industry when measuring and analysing Levels of Automation in their assembly systems.

'*The future assembly systems will consist of highly skilled operators...*' In order to choose and use the right level of automation, the choice itself has to be structured and well based. This thesis will discuss the importance of a structured method and an easy-to-use tool to visualise and quantify the levels of automation in the current state of a system. Furthermore, it will show how this could be used in a future analysis.

Lastly, this thesis will discuss the effects of changing mind-set from primary look at cost and productivity to also consider other parameters that could influence the system in order to be competitive.

Keywords: Levels of Automation, LoA, Assembly System, Quantify, Competitive, Cognitive

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Åsa Fasth

Guldheden, Gothenburg, February, 2012

LIST OF APPENDED PAPERS

The results presented in this thesis are primarily based on the work in the following appended papers.

Paper 1	**Fasth, Å.** and Stahre, J. (submitted 29 June, 2011), Task allocation in assembly systems –Measuring and analyzing Levels of Automation, *special issue* (Journal of Theoretical Issues in Ergonomics Science)
Contribution	*Fasth, Å. initiated the paper and wrote the paper with Stahre, J. as a reviewer.*
Paper 2	**Fasth, Å**. Stahre, J. and Dencker, K. (2008), Measuring and analyzing Levels of Automation in an assembly system. *Proceedings of the 41st CIRP International Conference on Manufacturing Systems (ICMS)*, Tokyo, Japan.
Contribution	*Fasth, Å. initiated the paper and wrote the paper with Stahre, J. and Dencker, K. as reviewers. Fasth, Å. was the corresponding author and presented the paper at the conference.*
Paper 3	**Fasth, Å.,** and Stahre, J., Does Levels of Automation need to be changed in an assembly system? - A case study. *Proceedings of the 2nd Swedish Production Symposium (SPS), Stockholm, Sweden, 2008.*
Contribution	*Fasth, Å. initiated the paper and wrote the paper with Stahre, J. as a reviewer. Fasth, Å. was the corresponding author and presented the paper at the conference.*
Paper 4	**Fasth, Å,** Reviewing methods for analyzing task allocation in a production system (*Accepted for publication*), *Journal of Logistic management*
Paper 5	**Fasth, Å.,** Bruch, J., Dencker, K., Stahre, J., Mårtensson, L. and Lundholm, T. (2010) Designing proactive assembly systems (ProAct) - Criteria and interaction between automation, information and competence, *Asian International Journal of Science and Technology in production and manufacturing engineering (AIJSTPME), vol 2 issue 4, pp.1-13*
Contribution	***Fasth, Å.** initiated the paper and wrote the paper with the other authors as reviewers. **Fasth, Å.,** Bruch, J., Dencker, K. collected the data and **Fasth, Å.** analysed it for the paper. Fasth, Å. was the corresponding author and presented the early version of the paper at the 42nd CIRP conference on manufacturing systems Grenoble, France, 2009.*
Paper 6	Fässberg, T., **Fasth, Å.,** Hellman, F., Davidsson, A., and Stahre, J (2012), Interactions between complexity, quality and cognitive automation, *4th CIRP Conference On Assembly Technology Systems*, Ann Arbor, USA
Contribution	*Fässberg, T., **Fasth, Å.**, Hellman, F., initiated the paper and wrote the paper with Davidsson, A., and Stahre, J. as reviewers.*

LIST OF ADDITIONAL PAPERS

1. **FASTH, Å.,** PROVOST, J., STAHRE, J. & LENNARTSON, B. (2012) From task allocation towards resource allocation when optimizing assembly systems. IN PATRAS, U. O. (Ed.) *45th CIRP Conference of Manufacturing Systems (CMS).* Athen, Greece.
2. MATTSSON, S., GULLANDER, P., HARLIN, U., BÄCKSTRAND, G., **FASTH, Å.** & DAVIDSSON, A. (2012) Perceived Production Complexity at Assembly Stations - A Case Study. IN PATRAS, U. O. (Ed.) *45th CIRP Conference of Manufacturing Systems (CMS).* Athen, Greece.
3. *FÄSSBERG, T., **FASTH, Å.**, HELLMAN, F., DAVIDSSON, A. & STAHRE, J. (2012) Interaction between Complexity, Quality and Cognitive Automation. 4th CIRP Conference on Assembly Technologies and Systems (CATS). Ann Arbor, USA.*
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5. PROVOST, J., **FASTH, Å**., STAHRE, J., LENNARTSON, B. & FABIAN, M. (2012) Human operator and robot resource modelling for planning purposes in assembly systems *4th CIRP Conference on Assembly Technologies and Systems (CATS).* Ann Arbor, USA.
6. ***FASTH, Å.*** *(accepted for publication) Reviewing methods for analysing task allocation in a production system. International journal of logistic management*
7. MATTSON, S., FÄSSBERG, T., STAHRE, J. & **FASTH, Å.** (2011) MEASURING INTERACTION USING LEVELS OF AUTOMATION OVER TIME. *21st International Conference on Production Research.* Stuttgart, Germany
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10. ***FASTH, Å****. & STAHRE, J. (Submitted) Task allocation in assembly systems - Measuring and analysing Levels of Automation. Special issue*
11. **FASTH, Å.** (2011) Comparing methods for design and measurement of production systems, *Proceedings of the 4th Swedish Production Symposium (SPS).* Lund, Sweden
12. FÄSSBERG, T., **FASTH, Å.,** MATTSSON, S. & STAHRE, J. (2011) Cognitive automation in mass customised assembly systems. *Proceedings of the 4th Swedish Production Symposium (SPS)*
13. **FASTH, Å.,** STAHRE, J. & DENCKER, K. (2010b) Level of automation analysis in manufacturing systems. *Proceedings of the 3rd international conference on applied human factors and ergonomics.* Miami, Florida, USA.
14. DENCKER, K., MÅRTENSSON, L. & **FASTH, Å.** (2010) ”The operator saves our day?” - Why do we need the operator? *Proceedings of the 3rd international conference on applied human factors and ergonomics.* Miami, Florida, USA.
15. **FASTH, Å.** & STAHRE, J. (2010) Concept model towards optimising Levels of Automation (LoA) in assembly systems. *Proceedings of the 3rd CIRP Conference on Assembly Technologies and Systems,* Trondheim, Norway
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18. ***FASTH, Å.,*** *BRUCH, J., DENCKER, K., STAHRE, J., MÅRTENSSON, L. & LUNDHOLM, T. (2010a) Designing proactive assembly systems (ProAct) - Criteria and interaction between automation, information, and competence Asian International Journal of Science and Technology in production and manufacturing engineering (AIJSTPME), 2 (4), 1-13.*
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1 INTRODUCTION

The aims of this chapter are to:

- *Introduce the reader to the research area and issues of Automation*
- *Describe research aim*
- *Formulate the research questions*
- *Describe the delimitations of the research scope in this thesis*

1.1 BACKGROUND

In order to maintain a sustainable production in an increasingly globalised industry, current traditions for design and usage of automation may not be adaptable to the needs and future challenges that the industry is facing. Manufacturing research has the potential to develop technologies for highly competitive manufacturing, adding value and sustainability by changing the orientation and the criteria of optimisation to support the structural change of manufacturing (Westkämper, 2008). Rapid changes of demands and requirements, both internal and external, frequently trigger plans for change in different manufacturing areas, i.e. lower product and production costs, higher quality and shorter throughput time. This demands a high degree of flexibility (Chryssolouris, 2006, Koren, et al., 1999) and more dynamic decision making later in the production chain. Flexibility and changeability are key enablers for meeting the challenges of a global market (Wiendahl, et al., 2007). Smaller batches and shorter time limits for set-up between products are normal demands on the assembly systems caused by increasing numbers of product variants, i.e. mass customisation. This results in increased amounts of information to and from the assembly personnel since information regarding every product variant needs to be available (Fässberg, et al., 2010). Furthermore the amount of information needed by the operators is individual and dependent on their level of expertise (Fjällström, 2007). As a result, there is a need for increasingly flexible methods for assembling products and means to make assembly systems more proactive. One solution could be to consider different levels of automation, both cognitive and physical.

In order to make the right decisions regarding the level of automation and obtain a competitive assembly system, companies have to know their present system, the future changes and how and what to improve in order to make the assembly system as effective as possible. Evolution of an assembly system is argued to be one of several steps towards a competitive position for a manufacturing company (Säfsten, 2002). A statement by Percy Barnevik in 1991 (Barnevik, 1991) is still applicable today:

> *"Modern technology has made it easy to copy products, but a process is not that easy to copy. A superior process can therefore give a more durable competitive advantage."*

An addition to this is the importance of highly skilled resources:

> "*... we expect that team assembly plants will be populated almost entirely by highly skilled problem solvers whose task will be to think continually of ways and means to make the system run more smoothly and productively." (Womack, et al., 1990)*

Throughout history, different strategies have been used in order to meet internal and external demands. The future is always hard to predict. If aiming for a more sustainable production, then a more effective and adaptive assembly system needs to be developed. One solution could be to consider different automation solutions, not necessarily to increase the automation, but to investigate pros and cons of the use of humans and technique.

1.2 Definitions of Automation

A broad spectrum of assembly systems with varying degrees of automation exists in industry today, such as manual assembly, semi-automatic assembly or automatic assembly (Rampersad, 1994). The term ‘automated assembly’ refers to the use of mechanised and automated devices to perform the various assembly tasks in an assembly line or cell (Groover, 2001). Depending on the context, the term automation has different meanings:*“...in their language, or in their region of the world or their professional domain, automation has a unique meaning and we are not sure it is the same meaning for other experts”(Nof, 2009)*. Furthermore, because automaton is context-dependent and because it describes technology that facilitates human performance, cognitive or physical, what is considered automation will therefore change over time.

The term automation evolves from ‘automatos’ in Greek which means *acting by itself* (Williams, 2009). The scope of this thesis will be limited to the final assembly system context within production systems and therefore the definitions and discussions about automation will also be limited to that context.

Automation can be defined as ‘*the execution by a machine agent (usually a computer) of a function that was previously carried out by a human’* (Parasuraman and Riley, 1997). This could be related to the more cognitive tasks of an assembly system. Another definition more related to the physical automation is: ‘*Automation is a way for humans to extend the capability of their tools and machines’* (Williams, 2009). A definition that could contain both the cognitive and physical automation is: *a technology by which a process or procedure is accomplished without human assistance* (Groover, 2001).

1.2.1 When to automate?

Mass customisation puts great strains on the product developers and the system designers. There are many different solutions available on the market today in terms of technologies and methodologies. Companies have to be at the front of the evolution in their field by adapting to future changes and trends, on both macro and micro level. ***But*** it is costly to invest in resources (both human and machines) and technology that will not be used to their full potential. Appropriate Levels of Automation (LoA), both cognitive and mechanical, must therefore be selected to meet the increased information flow and to avoid over or under automated systems. This means that suitable allocation of tasks between resources (human operators and machines) and technique has to be made and must be able to be dynamically changeable over time. One of the primary design dilemmas engineers and designers face is determining what level of automation should be introduced into a system that requires human intervention (Parasuraman and Riley, 1997).

Do companies think automation is an important factor to consider in order to be competitive?

Until recently, the primary criteria for applying automation were technological feasibility and cost. To the extent that automation could perform a function more efficiently, reliably, or accurately than the human operator, or merely replace the operator at a lower cost, automation has been applied at the highest level possible (Parasuraman and Riley, 1997). In line with Parasuraman and Riley, results from an industrial Delphi survey conducted in 2006 (Frohm, 2008) show that the top three answers regarding benefits with automation or when to automate were: cost savings, to get higher efficiency and to *increase competitiveness*. On the other hand, the top three answers regarding disadvantages with automation or when not to automate were: too many products or variants, investment cost, and adapting the product for manufacturing (Frohm, 2008).

In order for industry both to stay competitive and to handle the increasing demand of mass customisation, the question *when to automate* becomes a little more complex.

The assembly area is where most manual work takes place in the process. Humans and technology have to cooperate in order to simplify the job and make the overall system more efficient and productive. Companies must obtain deeper knowledge about new production solutions and be willing to evaluate them with reference to their own production in order to create a long-term sustainable system. One of the considerations preventing the total removal of human operators from systems has been the perception that humans are more flexible, adaptable, and creative than automation and thus are better able to respond to changing or unforeseen conditions (Parasuraman and Riley, 1997). Most system design tools focused solely on the physical system (Parasuraman, et al., 2000) towards a more flexible assembly (Feldmann and Slama, 2001) but all resources contributed to flexibility.

Completely automated systems almost always have a human operator somewhere, at some level (Dekker and Woods, 2002), so Chapanis' dream in 1970 (Chapanis, 1996), '*to automate everything you possibly can towards autonomous systems*', remains a dream, forty years later. Further, current research (Parasuraman and Wickens, 2008, Sheridan and Parasuraman, 2006, Stoessel, et al., 2008) argues that operators still have not been surpassed by conventional automation in terms of flexibility and high product variation. Therefore, operators should be used for more than supervision of machines and be integrated and seen as complementary to machines rather then divide the resources in man-machine thinking when performing task allocation in system production design (Hancock and Chignell, 1992, Hou, et al., 1993, Jordan, 1963, Kantowitz and Sorkin, 1987, Sheridan and Parasuraman, 2006).

In comparison with technical capabilities, human capabilities, human performance and cognition in automated systems are much less frequently described in literature or discussed in public forums (Parasuraman and Riley, 1997). Automation of physical functions has freed humans from many time-consuming and labour-intensive activities. However, full automation of cognitive functions such as decision making, planning, and creative thinking remains rare (Parasuraman and Riley, 1997). Flexible technology cannot be effective without flexible operators and vice versa (Slack, 2005) so humans and machines/technique should be seen as complementary, rather than conflicting, resources when designing a man-machine system (Jordan, 1963). The automation should aim for extending *the physical and cognitive* capacity of people to achieve what might otherwise be impossible (Lee, 2008).

1.2.2 THE IMPORTANCE OF QUANTIFYING

Existing methods used for designing assembly systems, do not consider LoA and different aspects regarding LoA as a prime parameter. To be able to compare current and future state and to turn the term and methods around level of automation from a "human factor" and design tool into an easy-to-use engineer tool, a more quantified method is needed. The key issue is not *who* make the decision or on *what* level the decisions are made, but *why* the decisions are made and upon *what* facts (Winroth, 2006). Case studies (Fasth and Stahre, 2008, Säfsten, 2002) show that these kind of decisions are often informal and unstructured. In order to make the decisions more objective and more structured, it is important to have a quantitative method to measure and analyse LoA.

1.3 Research aim and objective

As discussed, there are a lot of challenges when designing or improving an assembly system with regard to automation. There is a need for a structured method to determine *when* and *how much* to automate. The aim of this thesis is to show that:

> ***By quantifying, measuring and analysing physical and cognitive Levels of Automation, competitive assembly systems are enabled.***

1.4 Research questions

Based on the aim, the following three research questions (RQs) have been formulated;

RQ 1: Why is it important to quantify Levels of Automation (LoA) in an assembly system context?

The way companies choose and use their resources has been an issue ever since the craftsman became an operator, and the manual work became more automated. This research question will discuss why automation needs to be put in a quantitative context. Furthermore, the RQ will discuss why both the physical and cognitive automation need to be addressed when measuring and analysing an assembly system.

RQ 2: How should LoA be measured and analysed in assembly systems?

When the Levels of Automation have been quantified, this quantification could be used for further task allocation in an assembly system. The tasks in the assembly system are measured and analysed in a structured way in order to avoid under- or over-automated systems. This research question will explain the evolution from a method towards a more logical model aiming for presenting the measures and analyses of LoA, i.e. a concept model.

RQ 3: What are the expected effects of analysing and changing LoA?

Cost is a common parameter used when improving production systems. The final research question addresses the possible presence of other parameters linked to LoA that would provide equally good or better results than just focusing on cost when deciding if the LoA should be changed.

1.5 Delimitations

- The scope of this thesis is limited to the final assembly area of a production system.
  - Further, the shop-floor level is the primary scope.
- Product design will not be covered in this thesis
- Cost as a primary parameter will not be discussed in this thesis
- Even though production logistics is important to consider when redesigning a system it will not be discussed in detail in this thesis
- The thesis does not base its cognitive automation discussion on psychological theory
- The thesis does not discuss physical automation based on control theories, robotics engineering or computer science

1.6 OUTLINE OF THESIS

Chapter 1 provides the reader with a short introduction of the research area. Further, the research aim and research questions are presented.

Chapter 2 describes the research approach, i.e. the overall methodology used in order to reach the aim. Further, the methods used in the different papers in order to answer the research questions are presented.

Chapter 3 reviews earlier research and definitions that are used in the later part of the thesis and in the appended papers.

Chapter 4 presents the results from the appended papers correlated to each research question.

Chapter 5 discusses the overall aim, the research question in relation to the theoretical framework and the results from the appended papers.

Chapter 6 provides conclusions regarding the research aim.

2 RESEARCH APPROACH

This chapter presents the research design, thus providing a description of the diverse methods that were used to achieve the aim of the thesis.

2.1 RESEARCH METHODOLOGY

Research methodology means the strategy, path or design of the research, i.e. the choice of methods used to reach the aim (Crotty, 1998). The methods are the tools, i.e. techniques or procedures to analyse the gathered data and information related to the research questions (Crotty, 1998). The main methodology used in this thesis is applied research, which means that empirical data from industrial case studies are a major part of the research results. Independent related studies (Wilkinson, 1991) are also used as part of the research methodology, i.e. the theoretical framework and methods used are the same in all case studies but the research questions and discussion differ. This approach could also be referred to as a triangulation approach (Olsen, 2004), which aims to increase the quality of the research by mixing data or methods so that diverse viewpoints and standpoints cast light upon a topic. According to Deniz (Dezin, 1970), there are four different types of triangulation collections;

1. Data triangulation – Use of variety of data sources in a study
2. Investigator triangulation – Use of several different researchers or evaluators
3. Theory triangulation – Use of multiple perspectives to interpret a single set of data
4. Methodology triangulation – Use of multiple methods to study a single problem or phenomenon

The use of the different triangulation collections will be further explained in the sections below and within the discussion chapter, relation to the papers. But, as a summary, the different data sources used were production data gathered from production engineer at the companies and assessment of Levels of Automation within the stations in chosen production cells. In the case studies multiple researchers and in some cases master students collected the data and the information, explained more in detail in the empirical collection section. The theory collected is both from a quantitative perspective and a qualitative perspective (results discussed in paper 3). A multiple perspective has also been used when it comes to explain and discuss the view and use of Levels of Automation in assembly systems and in other areas such as control rooms etc (results discussed in paper 1). Further, paper 4 discusses the phenomenon of operators' action space, viewed from three different aspects (information flow to and from the operators group, level of competence and use of different levels of automation.). The gathering of this information was done by three different researchers which also resulted in an investigator triangulation.

2.2 RESEARCH PROCESS

The research in this thesis includes both a deductive research process (Patel and Davidsson, 2003) and an inductive research process (Starrin and Svensson, 1994). The process is illustrated in Figure 1. The first step is to formulate an overall aim with the research (purpose of research) in order to focus the theoretical and empirical collection; without such a research focus, it is easy to become overwhelmed by the volume of data (Eisenhardt, 1989). From both a theoretical collection and from empirical collections, a possible academic (theoretical) and industrial (empirical) gap is determined. These gaps are then formulated into a hypothesis which becomes RQs later in the process. The hypothesis is then synthesised (i.e. methodologies and methods are developed and validated within industrial case studies). Finally a more general methodology is developed and effects of its use are determined (theoretical and practical contribution).

The research process and the different types of triangulation used are illustrated in Figure 1.

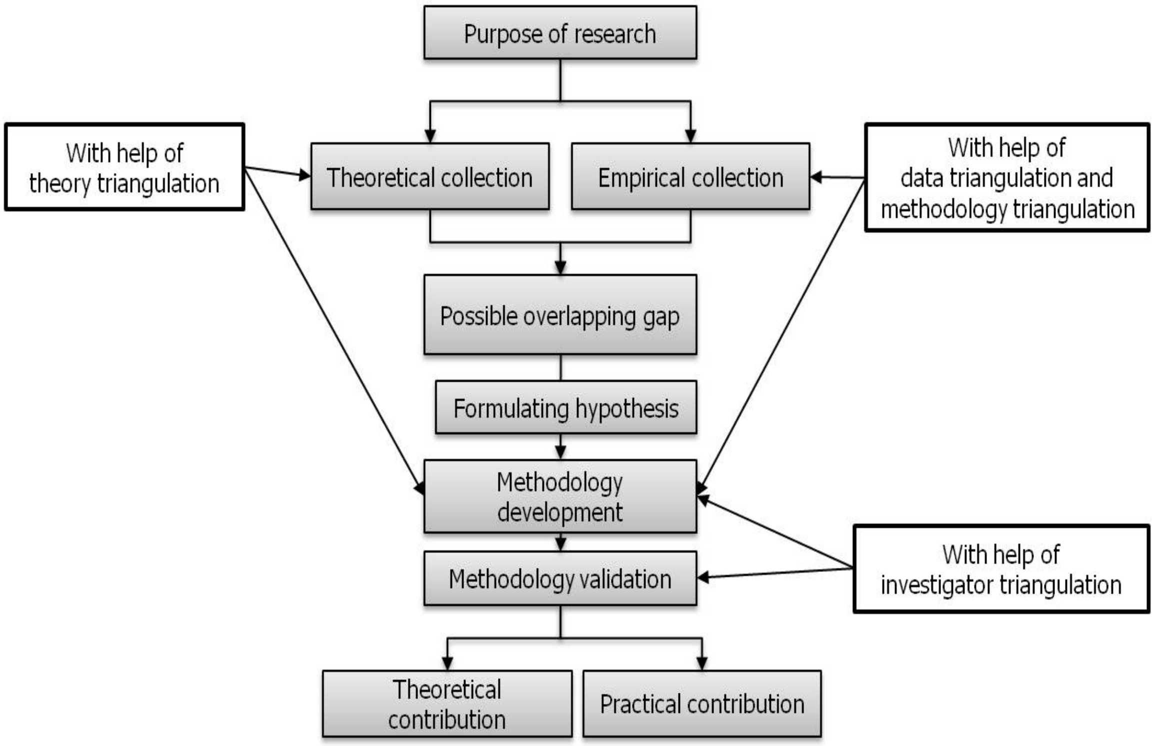


FIGURE 1 RESEARCH PROCESS, INSPIRED BY (EISENHARDT, 1989)

The following sections will describe the different areas and methods used in the research process.

The following sections will describe the different areas and methods used in the research process.

2.2.1 THEORETICAL COLLECTION

According to (Wacker, 1998) a theory (or theoretical framework) contains four components: (1) a domain where the theory applies, (2) definitions of terms or variables, (3) a set of relationships of variables and (4) specific predictions and factual claims.

Four areas have been chosen as a base for the theoretical framework and are connected to the components as follows:

The domain in this thesis is defined as Assembly systems. ***Definitions of terms and variables*** are related to the theoretical definitions of Levels of Automation (LoA) and ***the definition of set of relationships of variables*** are related to different effects usually measured and improved in an assembly system (excluding cost), i.e. time, productivity, flexibility, complexity. Further, the assessment variables could be seen as a relation between the different effects and LoA based on results from a method performing qualitative and/or quantitative assessments. The fourth component, specific predictions and factual claims (4), will be brought up in each theoretical area and in the discussion chapter.

The theoretical framework was gathered through secondary data (Merriam, 1994), i.e. books, papers (conference and journals), theses and reports.

2.2.2 EMPIRICAL COLLECTION AND ANALYSIS

A case study (or empirical collection) is done in order to investigate a current phenomenon within its real-life context. Case studies typically combine data collection methods such as archives, interviews, questionnaires, and observations. The evidence may be qualitative (e.g., words), quantitative (e.g., 534 numbers), or both (Eisenhardt, 1989). When the boundaries between the phenomenon and context are not clearly evident multiple sources of evidence are used (Yin, 2003).

In multiple case studies, detailed information is gathered at several sites, within the same company or at different companies (Flynn, et al., 1990). The empirical collection used in this thesis is thirteen industrial case studies that have been carried out from 2007 to 2011. Figure 2 illustrates when the case studies have been conducted, the relation to the appended papers and in what phase of the method development (i.e. DYNAMO++) they belong. The author has visited all companies and been part of all case studies, either as first part participant or as tutor for student thesis*

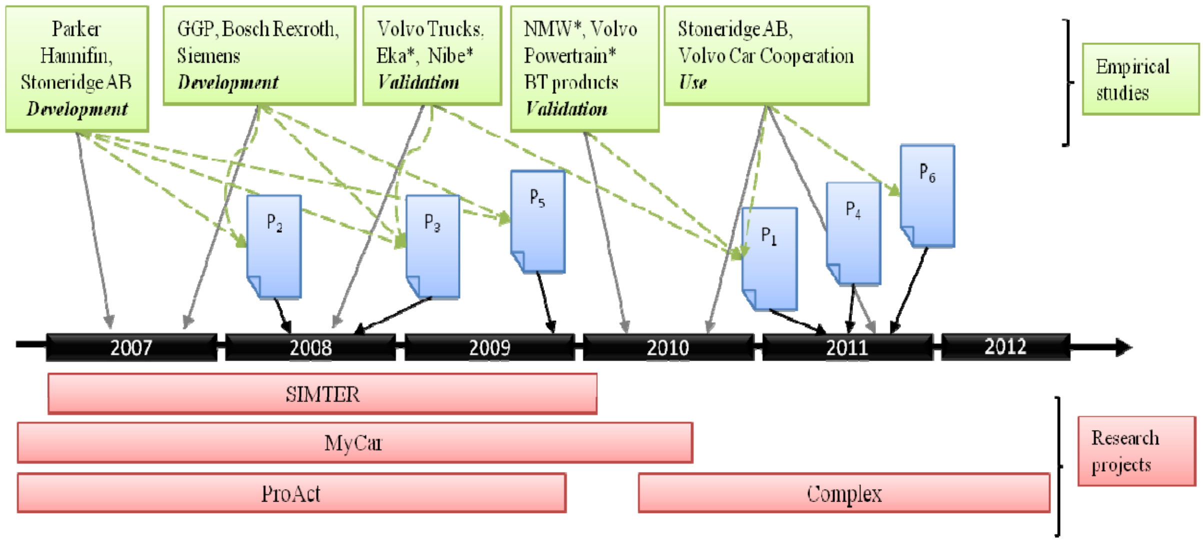


FIGURE 2 CASE STUDIES PERFORMED BETWEEN 2007 AND 2011

If there are enough cases, some forms of inferential statistical analysis are possible. The choice and number of cases should be decided with reference to the studied phenomena that are being examined, the context and the research questions posed (Easton and Harrison, 2004). In analysing the data, similarities and differences between companies are noted and documented, to the extent possible. For example, in (Fasth and Stahre, 2008), six of the thirteen case studies are compared in terms of triggers for change, lean awareness and production layout.

The empirical collection in the case studies has contained four different types of qualitative and quantitative methods, i.e. *Observations, Structured interviews, Measurements of cognitive and physical LoA and Workshops*. The methods are explained in the following sections.

Observations

In observational studies, the researcher can take either the role of non-participant observer (outside observer) or the role of participant observer (inside observer) (Sekaran, 2000) (Flynn, et al., 1990).

The approach in all case studies has been outside observation. Outside observation uses a neutral observer to collect data, often employing some methods for ensuring that data are collected systematically (Flynn, et al., 1990). The methods used for collecting data systematically have been interviews, measures and workshops. In some case studies, Value-Stream-Mapping (VSM) has been used in order to map the flow within the company.

Structured interviews

A structured interview involves the use of a form, which specifies questions to be used (Flynn, et al., 1990). The relevant questions and the order in which they are posed are decided in advance (Merriam, 1994). Other questions may be asked, as well, based on the direction of the conversation; however, certain questions are standard. Structured interviews permit comparisons between interviewees, without sacrificing the depth of the personal interview.
Structured interviews were performed in most of the case studies in the present thesis. All interviews were recorded and then transcribed. According to (Flynn, et al., 1990), the quality of the interview is raised significantly if the researcher does not have to take meticulous notes.
Other questions were covered by means of an open face-to-face interview with men and women from different professional categories, i.e. operators, production technicians, production logistics and production managers. Each interview took approximately 15-45 minutes. In-depth results and analysis from the interviews can be read about in other papers (Fasth, 2009, Fasth and Stahre, 2008).

Assessment of cognitive and physical Levels of Automation (LoA)

In order to measure cognitive (information and control) and physical (mechanical and equipment) levels, LoA, a taxonomy developed by Frohm (Frohm, 2008), was used. The taxonomy has seven steps for each type of LoA and different examples are used as guidelines, illustrated in Table 1.

TABLE 1 LOA-SCALES FOR COMPUTERIZED AND MECHANIZED TASKS WITHIN MANUFACTURING

LoA	Mechanical and Equipment	Information and Control
1	**Totally manual** - Totally manual work, no tools are used, only the users own muscle power. E.g. The users own muscle power	**Totally manual** - The user creates his/her own understanding for the situation, and develops his/her course of action based on his/her earlier experience and knowledge. E.g. The users earlier experience and knowledge
2	**Static hand tool** - Manual work with support of static tool. E.g. Screwdriver	**Decision giving** - The user gets information on what to do, or proposal on how the task can be achieved. E.g. Work order
3	**Flexible hand tool** - Manual work with support of flexible tool. E.g. Adjustable spanner	**Teaching** - The user gets instruction on how the task can be achieved. E.g. Checklists, manuals
4	**Automated hand tool** - Manual work with support of automated tool. E.g. Hydraulic bolt driver	**Questioning** - The technology question the execution, if the execution deviate from what the technology consider being suitable. E.g. Verification before action
5	**Static machine/workstation** - Automatic work by machine that is designed for a specific task. E.g. Lathe	**Supervision** - The technology calls for the users' attention, and direct it to the present task. E.g. Alarms
6	**Flexible machine/workstation** - Automatic work by machine that can be reconfigured for different tasks. E.g. CNC-machine	**Intervene** - The technology takes over and corrects the action, if the executions deviate from what the technology consider being suitable. E.g. Thermostat
7	**Totally automatic** - Totally automatic work, the machine solve all deviations or problems that occur by it self. E.g. Autonomous systems	**Totally automatic** - All information and control is handled by the technology. The user is never involved. E.g. Autonomous systems

Workshops

Workshops were performed at the end of each case study in order to present the result from the observations and measures, but also to get more information and ideas about the methodology and the system. The participants at the workshops were almost always the same that had been participating in the interviews (at some companies there could be different operators participating in the workshops and at interviews depending on availability from production). The number of participants was from 5 to 15 persons.

Validity

Validity is an assurance that the right thing is measured or to what degree the results are connected to reality (Merriam, 1994). Reliability could be explained as the accuracy of the measures (Sekaran, 2000) or to what degree the measures are repeatable (Merriam, 1994). According to Yin (Yin, 2003), validity could be determined by discussing four areas;

1. Construct validity – constructing correct measures for the concept that is being studied
2. Internal validity – establishing a causal relation
3. External validity – establishing a domain in which the study could be generalised
4. Reliability - ensuring that the operation of the study could be repeated with the same result

In the thesis validation was done foremost by the DYNAMO++ methodology and how to measure and analyse the cognitive and physical LoA. Because the research has been performed in multiple case studies within industry it is always hard to have 100% reliability because the industry and the environment are changing over time. A further discussion about validation of the methods used is done in Chapter 5.

2.2.3 THEORETICAL AND PRACTICAL CONTRIBUTION

The aim of this thesis could be seen from both a theoretical and a practical contribution. Theories are important for the social and natural sciences because they make possible robust explanations of previously or currently observed phenomena, and because they are points of departure for forecasts about future phenomena (May, et al., 2009). The research loop ends by adding new theory (or new pieces of the puzzle (Kuhn, 1962)) to the scientific world, i.e. theoretical contribution (otherwise it is not science (Danermark, et al., 2003)). On the other hand, when performing applied science the practical contribution is as important as the theoretical. In order to get the theoretical and methodology triangulation perspective, discussed earlier in this chapter, a discussion about the theoretical and practical contributions seen from a scientific and industrial perspective will be presented. Figure 3 illustrates the different areas and an explanation of the author's interpretation of each quadrant. The results or Research Answers (RAs) from the different quadrants will be shown in Chapter 4 and discussed in Chapter 5.

Theoretical	Definitions etc	Empirical validation
Practical	Operative and structure	Use and effect
	Scientific	Industrial

FIGURE 3 RELATIONS BETWEEN THE THEORETICAL AND PRACTICAL CONTRIBUTION FROM A SCIENTIFIC AND INDUSTRIAL PERSPECTIVE

3 THEORETICAL FRAMEWORK

This chapter presents four theoretical areas that have been chosen in order to reach the aim within this thesis.

3.1 ASSEMBLY SYSTEMS

There are numerous definitions of a manufacturing and production system. There are two main differences in the view of the definition of a manufacturing and production system. The first is that ***the manufacturing system is superior to the production system*** *(http://www.cirp.net, 2008).* The second definition, used in this thesis, is that ***the production system is superior to the manufacturing system***:

> *A production system is a collection of people, equipment and procedures organised to perform manufacturing operations at a company. A production system covers all steps in the chain from raw material to end costumer (Groover, 2001, Löfgren, 1983, Ståhl, 2006, Tangen, et al., 2008).*

Production systems can be divided into two categories or levels: facilities and manufacturing support systems; see Figure 4.

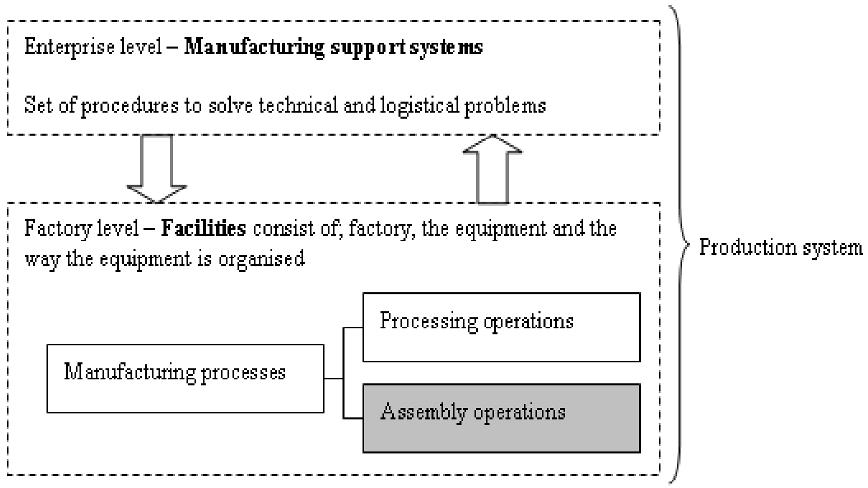


FIGURE 4 RELATIONS BETWEEN PRODUCTION AND MANUFACTURING SYSTEMS, AND ASSEMBLY OPERATIONS (GROOVER, 2001)

The processes that accomplish manufacturing involve a combination of machinery, tools, power and manual labour (Groover, 2001). The manufacturing processes can be divided into two different types: processing operations and assembly operations. ***Assembly operations*** generally have one material flow (Alting, 1978): *Converging flow*, corresponding to assembly or joining processes in which the shape is obtained by joining pre-shaped parts, without removing material to form a new entity. Components of the new entity are connected together either permanently or semi permanently (Groover, 2001).

The assembly system operates as an integral part of the total production system, which in turn consists of all the elements that support the manufacturing system (Cochran, 1998). The assembly system can be characterised as a transformation system, for the purpose of transforming (Bellgran, 1998) or converting (input) (Andreasen, et al., 1983) geometrically corresponding parts into subassemblies (Rampersad, 1994) or finished products (output) through manual and/or automated work tasks (Andreasen, et al., 1983). This integration is achieved by a process where the necessary operations are integrated in respect of material, energy and information (Andreasen, et al., 1983) that is given additional values, properties and qualities, so that the final state of the operations (Bellgran, 1998) is an organised unit working towards a goal (Andreasen, et al., 1983) that satisfies the previously declared need (Bellgran, 1998).

According to numerous research (Seliger, et al., 1987) (Westkämper, 2006) (Nyhuis, et al., 2005) (Wiendahl, 2002), a manufacturing system can be described from a hierarchical perspective, where every system can be divided into elements or stations. These can be further divided into part-elements or tasks. Figure 5 illustrates the hierarchical perspectives used in this thesis.

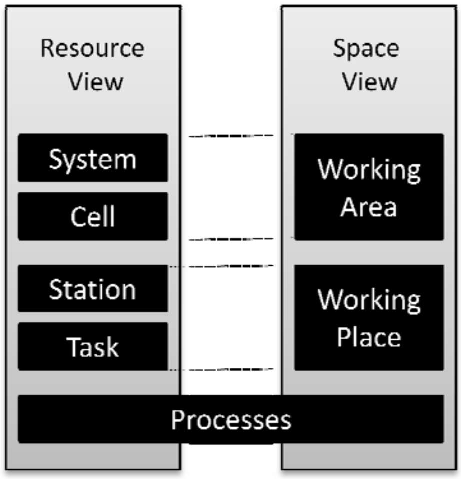


FIGURE 5 STRUCTURING LEVELS AND VIEWS OF A FACTORY (WIENDAHL, ET AL., 2007)**, EDITED.**

There are two structuring levels: working area and working place, and two views: the resource view proposal by Westkämper (Westkämper, 2006) and the space view proposal from Nyhuis (Nyhuis, et al., 2005) based on H-P Wiendahl (Wiendahl, 2002). Tasks within the working place has been added as a level in the model (Fasth, 2011), it is done to be able to in count task allocation.

3.2 ALLOCATION OF FUNCTION, TASK OR RESOURCE?

In order to optimize a system some kind of allocation has to be done. In most modern workplaces there is a close sharing of tasks between people and machines (Prince, 1985).
Throughout history there have been numerous of definitions according how and when to allocate a task or a function and to whom, man or machine?
One of the most common and debated attempt to allocate different tasks to different resources is fits list from 1951 (Fitts, 1951), which describes humans' and machines' differences. Fitts (Fitts, 1951) said that using the criteria in his list as the sole determinant of the allocation of functions was to lose sight of the basic nature of a system containing humans and machines. The Fitts list had little impact on engineering design practice because such criteria are overly general, non-quantitative, and incompatible with engineering concepts, and because they assume that functions will be performed by humans or machines alone (Prince, 1985). Jordan (Jordan, 1963) argued whether you could actually compare men and machines, and that the two should be seen as complementary, rather than conflicting, resources when designing a man-machine system. Sheridan (Sheridan, 1995) proposed to "allocate to the humans the tasks best suited to humans and allocate to the automation the task best suited to it. It is only when both humans and machine can do the same task, the question of task allocation becomes an issue (Hancock and Chignell, 1992). Contrary to the widely accepted urge towards autonomy, the real need is to provide an organic relationship for mutual benefit between the human and the machine (Tesar, 2002).

Today there are three different allocation approaches that are used in different stages and at different levels at companies, i.e. static and dynamic (adaptive) function allocation (Lagu and Landry, 2010), task allocation (Older, et al., 1997) and resource allocation (Isard, et al., 2009, Jain, et al., 1984).

The first kind of allocation, **function allocation (FA),** is mostly used early in the design phase before prototypes or design specification has been determined (Wright, et al., 2000); this makes this approach a little hard to use in real industry. Wirstad (1979) has summed up the FA process succinctly: "*Although the principle is clear, function allocation has never worked in practice"* (Fuld, 2000).

Task allocation of some kind is usually made later, often during system implementation (Cherns 1986,1987) (Waterson, et al., 2002). Different tasks could have multiple recourses suitable for it; Fasth (Fasth and Stahre, 2010) shows a LoA matrix, where both the physical and cognitive automation, current and future needed, could be illustrated and analysed. This type of allocation is often a static allocation based on global optimization. Suitable allocation of tasks between resources (human operators and machines) and technique has to be made and must be able to be dynamically changeable over time. However, it is common that designers automate every subsystem that leads to an economic benefit for that subsystem and leave the operator to manage the rest (Parasuraman and Wickens, 2008).

Generally, the manufacturing requirements of the product need to be matched to the capabilities of actual resources. This product/resource mapping means that one or more possible resources are identified for each product operation. The desired degree of flexibility will decide how many alternative resources are included in this **resource allocation**. Among the possible ones, a final choice has to be determined, e.g., by optimization (Lennartson, et al., 2010).
The resource allocation can be based on a simplistic model such as available/unavailable resources. Such a model can be easily applied if we suppose that there is no resource breakdown, no maintenance task, etc. In that case, a resource could be allocated to an operation as soon as it is available.

There is a need for a dynamic allocation that can take advantage of the access to instantaneous evaluation of the situations to choose the best allocation (Hoc, 2000).
A case study that uses dynamically changeable Levels of automation (LoAs) (Fasth, et al., 2008) shows that it is possible to change from a human operator to a robot-cell and vice versa in order to achieve volume and route flexibility. The issue to be shown in this paper is how to model and simulate this dynamic allocation when alternative resources could be allocated to some operations. Difference in LoA implies that different resources need to be modelled as precisely as possible so that these models correspond to these LoA and not to a global resource. Furthermore, models of behaviour, knowledge and skills for robots and human must be considered in different ways in order to better fit the real resources.

3.3 LEVELS OF AUTOMATION

A common industrial predisposition is to consider automation investments as "binary" decision, even though a simple choice between humans or machines for a specific task may be suboptimal. Several development trends towards highly automated production and shop floor workplaces were seen during the 1980's and early 1990's. At that time the predominant task allocation strategy was "left-over allocation". Since the late 1990's trends are changing, much due to obvious shortcomings of automation to fulfil cost and flexibility expectations.

Thus, to identify, implement, and maintain the correct level of automation in a controlled way could be a way to radically improve the effectiveness of a system. According to Frohm (2008), to make a manufacturing system as robust, flexible and adaptable as possible, the system must be resilient to process variations, such as the introduction of new products, tool changes, product disturbances etc. It is thus important to understand how to obtain a balanced manufacturing system that has the proper mix of operators and machines in order to e.g. obtain the highest profit possible without suffering loss of product quality. One way to achieve this balanced manufacturing system is to separate the system description into two basic classes of activities, i.e. information handling and physical work. The next step would then be to describe the allocation of tasks within each class, i.e. the "level of automation".

Extensive amounts of research have been done in the area of levels of automation, emphasising different perspectives. Automation research can be divided into three main groups, i.e.

- **Mechanical** automation (Duncheon, 2002, Groover, 2001, Kern and Schumann, 1985, March and Mannari, 1981)
- **Information and control** automation (Bright, 1958, Endsley, 1997, Hollnagel, 2003, Parasuraman, et al., 2000, Parasuraman and Wickens, 2008, Sheridan, 1992).
- **Combinations** of physical/mechanical and information/cognitive automation (Frohm, 2008).

To determine what to automate, a classical task allocation strategy from 1951 (the MABA-MABA list) was proposed by Fitts (Fitts, 1951). It was an attempt to suggest allocation of tasks between humans and machines by treating them as system resources, each with different capabilities. Two examples, i.e. "*M*achines *A*re *B*etter *A*t" performing repetitive and routine tasks while "*M*en *A*re *B*etter *A*t" improvising and using flexible procedures. At the time, this was a revolutionary thought causing a lot of debate.

Jordan (Jordan, 1963) argued whether you could actually compare man and machine, and that the two should be seen as complementary rather than conflicting resources when designing a man-machine system. Sheridan (Sheridan, 1995) proposed to "allocate to the human the tasks best suited to humans and allocate to the automation the task best suited to it." But if tasks in which machines are better become automated and operators are still required to monitor the automation, maintaining full situation awareness (Endsley and Kiris, 1995), we might lose more than we gain. Fifty years after Fitts published his list, Hollnagel (Hollnagel, 2003) argues that the machine (or automation) has been used for three main purposes over the years (which is in line with Fitts), i.e. to ensure more precise performance of a given function; to improve stability of performance by relieving people of repetitive and monotonous tasks; and to enable processes to be carried out faster and more efficiently. So, do Fitts' thoughts still prevail, or has research turned towards Jordan's argument?

The decision matrix suggested by Prince (Prince, 1985) was partly in line with Fitts in that some tasks were better performed by machines and some better by humans. But interestingly Prince also defined a set of tasks where the same task could and should be performed both by humans and by machines. Further, when there is no single allocation, the different resources need support from each other, which is in line with Jordan's argument. Hancock (Hancock and Chignell, 1992) argues that it is only when both human and machine can do the same task that the question of task allocation becomes an issue. In line with Jordan, previous research (Hancock and Chignell, 1992, Hou, et al., 1993, Kantowitz and Sorkin, 1987, Sheridan, 2000) agrees that the task allocation should be seen as complementary between man and machine rather than assigning tasks solely to one resource**.** Thus, suitable allocation of tasks between resources (human operators and machines) and technique has to be made and must be able to be dynamically changeable over time. However, it is common that designers automate every subsystem which leads to an economic benefit for that subsystem but leaves the operator to manage the rest (Parasuraman and Wickens, 2008). Parasuraman et al. (Parasuraman, et al., 2000) argue that automation design is not an exact science; however, neither does it belong in the realm of the creative arts, with successful design dependent upon the vision and brilliance of individual creative designers.

Table 2, show a summary of definitions of levels of automation from each decade, from 1950 to 2010.

TABLE 2 SUMMARY OF DEFINITIONS OF LEVELS OF AUTOMATION (FROHM, ET AL., 2008), EDITED

Author	Definition of Levels of Automation	Mechanical scale	Information and control scale
(Bright, 1958)	Divides the levels depending on who initiates the control, the human (1-4),the human together with automation (5-8) or the automation (9-17)	17	-
(Amber and Amber, 1962)	The extent to which human energy and control over the production process are replaced by machines	-	-
(Williams, 1977)	Automation is the capability of causing a machine to carry out a specific operation on command from an external source	-	5
(Sheridan, 1980)	The level of automation incorporates the issue of feedback, as well as relative sharing of functions in ten stages	-	10
(March and Mannari, 1981)	Automaticity is defined in six levels from conducting the tasks manual, without any physical support, to fully automated cognition with computer control	6	
(Kern and Schumann, 1985)	Degree of mechanization is defined as the technical level in five different dimensions or work functions	3 (9)	
(Billings, 1997)	The level of automation goes from direct manual control to largely autonomous operation, where the human role is minimal		6
(Endsley, 1997)	The level of automation in the context of expert systems is most applicable to cognitive tasks such as ability to respond to, and make decisions based on, system information	10	5
(Satchell, 1998)	The level of automation is defined as the sharing between the human and machines, with different degrees of human involvement		
(Parasuraman, et al., 2000)	The interaction and task division between the human and the machine should instead be viewed as a changeable factor which can be called the level of automation.		10+4
(Groover, 2001)	Level of mechanization can be defined as the manning level, with focus on the machines	3	
(Duncheon, 2002)	'Manual' tasks are those in which humans are responsible for conducting the task. 'Semi-automatic' is a higher level of automation and involves automated alignment and application by a robot. 'Automatic', where material handling is also automated.	3(6)	
(Frohm, et al., 2008)	The allocation of physical and cognitive tasks between humans and technology, described as a continuum ranging from totally manual to totally automatic	7	7

3.4 ASSESSMENT METHODS

In Paper 3, ten assessment methods have been reviewed. A summary of the methods (except DYNAMO++) is presented in the following two sections, divided into quantitative and qualitative methods.

3.4.1 QUALITATIVE VERSUS QUANTITATIVE

The aim with a qualitative method is to interpret and understand a phenomenon (Patel and Davidsson, 2003). The research is done by asking the “journalist triangle” plus two questions, i.e. why, what, who + when and where. A quantitative method could be described as gathering data that will be transformed into figures and numbers to enable statistical analysis (Holme and Solvang, 1997). The two approaches have different pros and cons depending on in what context the method is going to be used.

Of course there are extremists in this matter:

> *"There's no such thing as qualitative data. Everything is either 1 or 0"* (Kerlinger, 1960)
>
> and
>
> "*All research ultimately has a qualitative grounding*" (Campbell, December,1976)

Table 3 shows the main differences between the qualitative and quantitative approach.

TABLE 3 FEATURES OF QUALITATIVE AND QUANTITATIVE METHODOLOGY (MILES AND HUBERMAN, 1994)

Qualitative	Quantitative
The aim is a complete, detailed description.	The aim is to classify features, count them, and construct statistical models in an attempt to explain what is observed.
Researcher may only know roughly in advance what he/she is looking for.	Researcher knows clearly in advance what he/she is looking for.
Recommended during earlier phases of research projects.	Recommended during later phases of research projects.
The design emerges as the study unfolds.	All aspects of the study are carefully designed before data are collected.
Researcher is the data-gathering instrument.	Researcher uses tools, such as questionnaires or equipment, to collect numerical data.
Data are in the form of words, pictures or objects.	Data are in the form of numbers and statistics.
Subjective Individuals’ interpretation of events is important, e.g., using participant observation, in-depth interviews etc.	Objective Seeks precise measurement & analysis of target concepts, e.g., uses surveys, questionnaires etc.
Qualitative data are more 'rich', time-consuming, and less able to be generalized.	Quantitative data are more efficient, able to test hypotheses, but may miss contextual detail.
Researcher tends to become subjectively immersed in the subject matter.	Researcher tends to remain objectively separated from the subject matter.

The following sections contain theory about nine different assessment methods used as a comparison to DYNAMO++ methodology in paper 4.

A model for types and levels of human interaction with automation (Parasuraman, et al., 2000, Parasuraman and Wickens, 2008)

The model is primarily used to analyze ATC (Air Trafic Control) systems with the issue: given specific technical capabilities, which system functions should be automated and to what extent? The human performance consequences of specific types and levels of automation constitute the primary evaluative criteria for automation design using the model. Secondary evaluative criteria include automation reliability and the costs of action consequences. Such a combined approach—distinguishing types and levels of automation and applying evaluative criteria—can allow the designer to determine what should be automated in a particular system. The model does not *prescribe* what should and should not be automated in a particular system. Hence, the model provides a more complete and objective basis for automation design than approaches based purely on technological capability or economic considerations. Ten levels of automation of decision and action selection are used for task allocation.

Complementary Analysis and Design of Production Tasks in Socio-technical Systems (KOMPASS) (Grote, 2004, Wäfler, et al., 1997)

The main aim with the COMPASS method is to design production systems where a human has control over technology, i.e. automated systems. Expert analysis of existing systems is done based on three levels of analysis criteria; work system, human work tasks and human machine system. The method is built on the complementary principle (Jordan, 1963) when designing a system, i.e. humans and machines are fundamentally different and can therefore not be compared on a quantitative basis but complement each other, performing tasks in a joint cognitive system (Hollnagel and Woods, 2005).

Cognitive Reliability and Error Analysis Method (CREAM) (Hollnagel, 1996, Hollnagel, 1998)

CREAM is a Human Reliability Analysis (HRA) method, i.e. modeling cognitive errors and error mechanisms into the risk assessment processes. The basic notion is that of contextual control modelling, i.e., describing human cognition in terms of the competence for actions and the way in which the actions are controlled. CREAM can be used to identify the most likely cause of an observed event--either an accident or an erroneous action. The method can also be used in a predictive way to derive the likely consequences of specific erroneous actions.

Task Evaluation and analysis Methodology (TEAM) (Johansson, 1994, Wäfler, et al., 1997)

The method was developed between 1994 and 1996. The main aim is to evaluate existing advanced manufacturing systems (AMS) from a user perspective in order to pinpoint efficiency problem areas. Further to provide support for humans to better interact with complex technology (Wäfler, et al., 1997). Task analysis is presented in an evaluation matrix, developed by Stahre (Stahre, 1995), based on a combination between Sheridan's supervisory control and Rasmussen's human behaviour levels. Four factors are considered: work environment, work tasks, information flow and system performance (Johansson, 1994). The method should ideally be performed by multidimensional system design teams with at least one human factor specialist. Three levels are used for task evaluation: 1) generally difficult, 2) differentially difficult, 3) tasks known by few operators

Taxonomy for Cognitive Work Analysis (Rasmussen, 1985, Rasmussen, et al., 1990)

This taxonomy was first published in 80s and should be used for effective support of decision processes to create a work practise that suits the individual users' cognitive resources (Rasmussen, et al., 1990). A work domain should be represented at five levels of abstraction, representing goals and requirements, general functions, physical processes and activities, as well as material resources (Rasmussen, et al., 1990). Any of these levels has a work function (*what* should be used) which can be seen both as a goal (*why* it is relevant) for a function at a lower level, and as a means for a function at a higher level (*how* this is realized), (Rasmussen, et al., 1994). Moving from a lower level to a higher level of abstraction means a change in the representation of system properties.

TUTKA production assessment tool (Koho, 2010)

The TUTKA production assessment tool was developed during the end of 2000s. The main aim with the tool is to assess the current state of a production system and to identify potential and means for improvements. The tool is comparing the current state of the system with a desired state, i.e. a well performed production system, by using 33 key characteristics, 6 decision areas and 6 production objectives.

Systematic Production Analysis (SPA) (Ståhl, 2007)

The SPA was developed in 2007-2008 with focus on manufacturing processes such as machining. The main aim is to measure the existing production condition and to simulate (Jönsson, et al., 2008) different outcomes regarding three main parameters, i.e. Quality (Q), Down-time parameters (S) and Production speed/tact (P) in order to reduce cost. The methodology has also been used in assembly operations (Andersson, et al., 2009), focusing on capacity flexibility and part cost. Two levels of automation is used to describe the assembly stations (manual/ automatic).

Productivity Potential Assessment (PPA) (Almström and Kinnander, 2007 , Almström and Kinnander, 2009)

The PPA method was developed during 2005-2006 by the institute of innovation and management at Chalmers University of Technology, Sweden. The main aim is to show the improvement potential of productivity in Swedish manufacturing companies. The parameters forming the PPA-method are divided into different 4 levels:

- Level 1 is the core of the method, constituting two parameters for measuring efficiency in manual work and machine work respectively.
- Level 2 parameters affect productivity at corporate level,
- Level 3 parameters indicate the company's ability to improve the production while maintaining a sound work environment.
- Level 4 treats the potential of improving productivity

Four levels of (mechanical) automation are used:

1) Man- Manual,

2) Semi – Semi-automatic

3) Auto – Automatic

4) Proc – Process industry

Lean Customisation Rapid Assessment (LCRA) (Comstock, 2004)

This method is a further development of the Rapid Plant Assessment (RPA) method, which was developed to help managers to fast determine if a factory was lean or not and discern the factory's strength and weaknesses where (Goodson, 2002). The main aim with the further develop method, LCRA, is to provide support in the analysis and/or design of a production system or even en entire company for mass customisation (Comstock and Bröte, 2003). This is done through three evaluation sheets divided into costumer elicitation, engineering and manufacturing.

3.4.2 DYNAMO

The main aim with this method was to investigate how decisions of automation was made and to work out a possible framework for design, measuring and visulise automation to be used for strategy decisions in order to achieve dynamic automation in manufacturing (Säfsten, et al., 2007, Winroth, et al., 2005). The DYNAMO method was developed during 2004 to 2007 with help of six case studies and validated with a seventh (except the last step) (Granell, et al., 2007). The DYNAMO method contains of eight steps, resulting in minimum and maximum levels of the company's automation strategy. This method could be seen mostly as a qualitative method because the tools used are interviews and observations. The taxonomy (se chapter 2) containing seven grades are used as a reference scale for the observations.

3.5 Effects

The following sections will discuss different types of effects in an assembly system, both direct measurable and indirect measurable parameters. As described in the delimitations in chapter 1, cost is off course the primary KPI and the desired parameter to effect. Because it is primary it is will not be discussed nor brought up in this chapter, but seen as an effect of changing the secondary effects and LoA.

3.5.1 Time

Measuring different time parameters has always been important in industry. The basis for measurements and methods started with F.W Taylors scientific management (Taylor, 1911), motion studies by Frank and Lillian Gilbreth (Gilbreth, 1911) and later the MTM (Method-Time-Measurement) by H.B Maynard in 1917 (Bicheno, 2006, Smith, 2004).

While the Gilbreths' motion study work is commonly linked with Frederick Taylor's time studies and grouped within the various "laws and principles" of scientific management, in reality there is a great difference between the two. The components which was originally known as the "Taylor system" and later became scientific management changed how workers where paid, introduced a new division of labour, as well as expanded and strengthened the role of management. The use of stop watches to measure and set the proper time for tasks was important, but only as part of the overall system. The Gilbreths' motion studies where more focused on how a task was done, and how best to eliminate unnecessary, tiring steps in a process. The main difference between time studies and MTM is that in the former, the time to perform a task is measured while in MTM an average time is calculated based on different motions, which means that you do not have to measure on the shop floor to gain a first hint of how long the task takes. Today, measurement is mainly used for planning, but also to balance tact lines. This thesis focuses on three time parameters, which are described briefly below.

- **Cycle time** -The time it takes to manufacture one individual product, (Mattson, 2004) and for the operator to finish all of his/hers work tasks (Rother and Shook, 2002).
- **Operation time** - Operation time is referred to the lead-time for carrying out one manufacturing step. It includes waiting time, transport and handling time to the production group, queue time in the production group, set-up time and production time. It represents one part of the throughput time. (Mattson, 2004)

- **Throughput time** - The throughput time is the time it takes to manufacture an article from material and start of the first operation to delivery of a finished quality approved product. The throughput time is a part of the lead time and includes transport times, queuing time, set-up time and producing time (Mattson, 2004).

3.5.2 Flexibility

An early definition of flexibility was provided by Stigler (1939) who defined it as: "*Those attributes of a manufacturing technology which can accommodate grater output variations*". Since then, numerous definitions of flexibility have been suggested. Sethi and Sethi (1990) demonstrated the use of over 50 separate terms describing flexibility. Slack stated that flexibility is above all other measures of manufacturing performance, cited as a solution (Slack, 2005). More flexibility in manufacturing operations means more ability to adapt to customer needs, respond to competitive pressures, and to be closer to the market (Slack, 2005). The types of flexibility that will be discussed in this thesis are Volume flexibility, Routing flexibility and Production flexibility.

Table 4 shows definitions of these three types of flexibilities from different perspectives

TABLE 4 DEFINITIONS OF FLEXIBILITY

Authors	Volume Flexibility	Product Flexibility	Routing Flexibility
(Gerwin, 1983)	The ability to handle a change in volume for a specific unit.	The ability to add and remove details from the mix over time	The ability to reroute a product's path if a unit doesn't work.
(Browne, et al., 1984)	The ability to manufacture profitably in spite of a shifting manufacture volume.	The ability to manufacture a product in an economical way.	The ability to continue manufactures a product in spite of a tool breakdown.
(Mattson, 2004)	A company's ability to adjust to variations in demand volumes.	A company's ability be able to produce customised products within a given product concept and lead-time that fulfil customer demands for variation	An operation that could be used as an alternative manufacturing step in another production group if the usual operation and production group are unavailable or unusable due to under capacity or machine breakdown
(Slack, 2005)	The ability to change the level of aggregated output	The ability to introduce novel products, or to modify existing ones.	-
(Ståhl, 2006)	The ability to change production volume while retaining the effectiveness and the moving costs tied to the production tact.	The ability to develop, buy and produce new products and to modify the product and the assembly system for normal and nominal production.	The ability to produce a multitude of products and handle changes in production planning.

3.5.3 Proactivity

According to (Frese and Fay, 2001), research focuses on reactive performance concepts, where people have to fit given tasks. Occurring needs and solutions become responses to existing problems, i.e. highly reactive actions. The introduction and ramp-up of a new product is often a discrete and unique event rather than part of the long-term development of the assembly system. It is questionable whether the reactive approach is sufficiently progressive and competitive. Instead, assembly systems need to be dynamic and evolvable to really constitute long-term assets for the manufacturing company (Onori, et al., 2006). Consequently, the preferred assembly system should have the ability to proactively meet emergent and long-term fluctuations. In dynamic environments, the activities of the operators' job are no longer fixed and the work situations he/she faces are unlikely to be identified by work instruction sheets. It is assumed that assembly work settings enabling proactive behaviour on the part of the human operators, which is important for managing the increasing uncertainty of work contexts (Griffin, et al., 2007).

The approach is based on the concept of proactivity: the ability of operators to control a situation by taking action and effectuating changes in advance ensuring a favourable outcome (Dencker, et al., 2007). This is in line with (Griffin, et al., 2007), who defined proactivity as:

> *"the extent to which the individual takes self-directed action to anticipate or initiate change in the work system or work roles"*

In work situations characterised by uncertainty, where aspects of work roles cannot be formalised, a proactive assembly system with a focus on active operator participation may be favourable and is supported by several studies [see e.g. (Crant, 2000, Dencker, et al., 2007, Frese and Fay, 2001, Parker, et al., 2006)] (Bruch, et al., 2008).

Proactive behaviour by operators supports both the short and long term development of proactive assembly systems (Crant, 2000) stated that

> *"Proactive behaviour can be a high-leverage concept rather than just another management fad, and can result in increased organizational effectiveness"*

Proactive behaviour can be characterised by 1) anticipation of problems related to change, 2) initiation of activities that lead to a solution of the change-related problems and improvements in the work, and 3) resolution of change-related problems (Sherehiy, et al., 2007).

Proactive operators' decisions are influenced by clues, early warnings, uncertain information, lack of information and the overall objectives. The latter is important, as proactive operators are expected to have a long-term view of and anticipatory perspective on the development of their work place (Bruch, et al., 2007). Such a system consists of technical components efficiently integrated with human operators to constitute reliable resources in the manufacturing system. In this way, present and future requirements for sustainability, flexibility and robustness can be met (Dencker, et al., conditionally accepted for publication). The effect of predicted and unpredicted disturbances can be minimized, thus enhancing the availability of the entire assembly system (Flegel, et al., 2005). Unfortunately, the use of proactivity as a competitive factor in assembly system design is not widespread (Dencker, et al., 2009)

3.5.4 COMPLEXITY

Complexity can be defined as: "*the complexity of a system is the degree of difficulty in predicting the system properties, given the properties of the system's parts*" (Weaver, 1948). Complexity can be divided into three sub parts, illustrated in Figure 6.

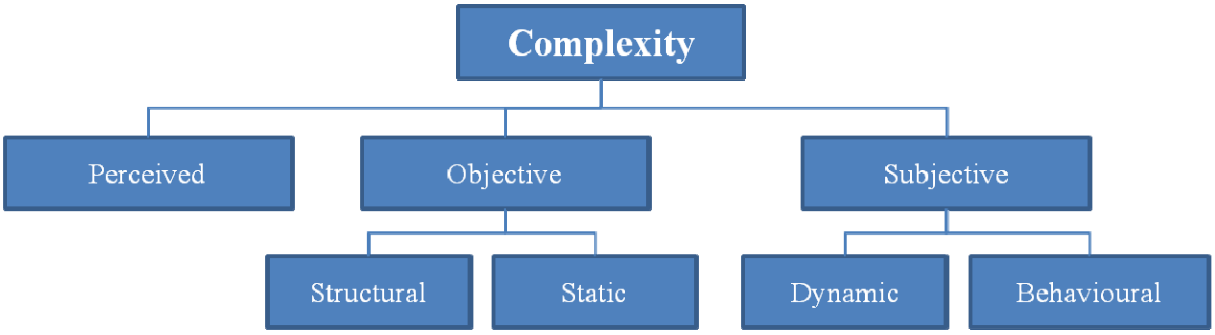


FIGURE 6 ILLUSTRATES A DIVISION OF COMPLEXITY INTO PERCEIVED, OBJECTIVE AND SUBJECTIVE COMPLEXITY

Perceived complexity is in research closely related to managing and handling critical events, production disturbances, frequent changes, unknown situations, unpredicted situations, and difficult work tasks etc. [6-8]. Hence, as production systems become more complex there is more that can go wrong, in several ways, and it is increasingly difficult to predict faults [9]. Human cognitive skills at different levels in the organization are increasingly crucial when manufacturing systems are becoming increasingly complex and subjected to changes and uncertainties [10].

Objective complexity can be further divided into**:**

- *structural complexity* Blecker et al. (Blecker, et al., 2005)or *static complexity* Frizelle (Frizelle and Suhov, 2001). Characteristics are related to fixed nature of products, hierarchical structures, processes, variety, and strength of interactions.
- *Behavioral complexity* (Asan, 2009) is characterized by dynamism, nonlinearity, deviation from equilibrium, history, adaptive, emergent structures, and self-organisation evolution. *Dynamic complexity*, which is caused by external and internal sources within the operation, like variations in dates and amounts due to material shortness, breakdowns, insufficient supplier reliability.

Regarding *subjective production complexity*, the same production system or situation may be perceived differently depending on a number of different factors such as individuals´ skills, competence and experience (Fässberg, et al., 2011).

4 RESULTS

This chapter presents the results from each paper, how these are related to the research questions and the four theoretical areas.

Table 5 shows a summary of contribution of each paper in relation to the three RQs and the theoretical areas, brought up in previous chapter.

TABLE 5 HOW THE PAPERS CONTRIBUTE TO THE RQ:S AND THEORETICAL AREAS

	Theoretical and practical contribution				
	Levels of Automation	Assessment methods	Effects	Assembly systems	Comments and contribution
RQ 1	**x**	**x**			***Why is it important to quantify Levels of Automation (LoA) in an assembly system context?***
Paper 1	x	x			P_1 present result from a literature study done to describe the lack of quantitative methods when assessing Levels of automation in assembly systems.
Paper 4	x	x			P_4 reviews ten assessment methods thru a literature study to determine if these models are assessing LoA and so, if this is done quantitative or qualitative.
RQ 2	**x**	**x**			***How should LoA be quantified, measured and analysed in assembly systems?***
Paper 2	x	x			P_2 present a methodology, DYNAMO++, for measuring and analysing LoA based on five case studies and a literature review.
Paper 3		x			P_3 presents results from seven case studies using DYNAMO++
Paper 5	x	x			P_5 is introducing the ProAct meta model which describe the relation between automation, information and competence. This is a further development of the methodology described in P_2.
Paper 1	x	x			P_1 describe a concept model containing a main loop for measuring and analysing LoA and other important areas to consider when doing a task allocation between resources. A further development of the meta methodology presented in P_4.
RQ 3	**x**		**x**	**x**	***What are the expected effects of analysing and changing LoA?***
Paper 3			x	x	P_3 presents results from seven case studies to determine if to change LoA in order to achieve the triggers for change
Paper 1	x		x		Considering LoA related to Time and Flexibility
Paper 5	x		x	x	P_5 presents how LoA could affect Proactivity
Paper 6			x	x	P_6 is describing thru an industrial case study, the relations between assembly errors, complexity and LoA and how to quantify these in an assembly context.

The sections below summarises the appended papers in relation to the RQs

4.1 Results related to RQ1

The sections below will give a short description of the most important results in the papers related to RQ1: ***Why is it important to quantify Levels of Automation (LoA) in an assembly system context?***

The way companies choose and use their resources has been an issue ever since the craftsman became an operator, and the manual work became more automated. This research question will discuss why automation needs to be put in a quantitative context. Furthermore, why both the physical and cognitive automation needs to be addressed when measuring, analyzing and improving an assembly system.

4.1.1 Paper 1[1]

The aim of this paper was to describe the need for quantitative methods when wanting to measure and analyse different automation solutions in assembly systems. The part of the paper related to RQ1 is based on literature studies.

According to Fasth et al (Fasth and Stahre, 2008) and Säfsten et al. (Bellgran and Säfsten, 2005, Säfsten and Aresu, 2000), a majority of companies studied, have a clear picture of why to change their system. However, the evaluations are often informal and unstructured, i.e. interpretation rather than facts. To choose solutions based solely on experience and interpretation rather than facts and numbers might not be the optimal solution when designing a system. A more reliable and objective quantitative method is therefore needed.

A problem related to MABA-MABA-oriented methods is the simplicity e.g. "*put your allocation problem into the method and the solution will emerge from the other end*" (Dekker and Woods, 2002). The methods do not really explain the cognitive actions for how and when to intervene, nor do they describe how to switch from level to level. The relevance of a task allocation process is obvious, yet there is still lack of systematic methods and, more importantly, methods that can be applied to advanced technological systems (Older, et al., 1997)**.** Another problem with new methods and tools in the human factors area concerns their lack of uptake and use by system developers. New methods must therefore be developed jointly with its users, i.e. adaptable to be put in practice (Older, et al., 1997, Waterson, et al., 2002), furthermore the method must be validated within its planned area of use.

The paper compares requirements from (Older, et al., 1997, Waterson, et al., 2002) with the concept model developed by (Fasth and Stahre, 2010) in order to see if the concept model is fulfilling them. The concept model and the validation of the model are described under RQ2.

The taxonomy is a seven-step reference scale, for cognitive and physical LoA aiming at quantifying tasks with help of different Levels of Automation. Frohm (Frohm, et al., 2008) defined physical tasks as the level of automation for mechanical activities, *mechanical LoA,* while the level of cognitive tasks is called *information LoA.* Mechanical LoA is *WITH WHAT* to assemble, while Cognitive LoA is *HOW* to assemble on the lower levels (1-3) and *situation control* on the higher level (4-7) (Fasth and Stahre, 2008).

[1] Fasth, Å. and Stahre, J. (submitted 29 June, 2011), Task allocation in assembly systems –Measuring and analyzing Levels of Automation, *special issue* (Theoretical Issues in Ergonomics Science)

A matrix integrating the two reference scales, as seen in figure 7, forms a 7x7 matrix, resulting in 49 possible types of solutions for task allocation, each including a physical LoA and a cognitive LoA. The figure displays the division between human and machine assembling and monitoring the tasks.

Machine assembling – A machine is performing the task and a human has a monitoring role or no role at all (in totally autonomous systems)

Human assembling and monitoring – A human is performing the task and also monitoring her own work (or has no technique helping her monitoring the work)

Machine/technique monitoring – A machine or technique is monitoring the task performed either by human or machine.

When the machine/technique is both performing and monitoring the task, humans could still have a superior monitoring on station or factory level.

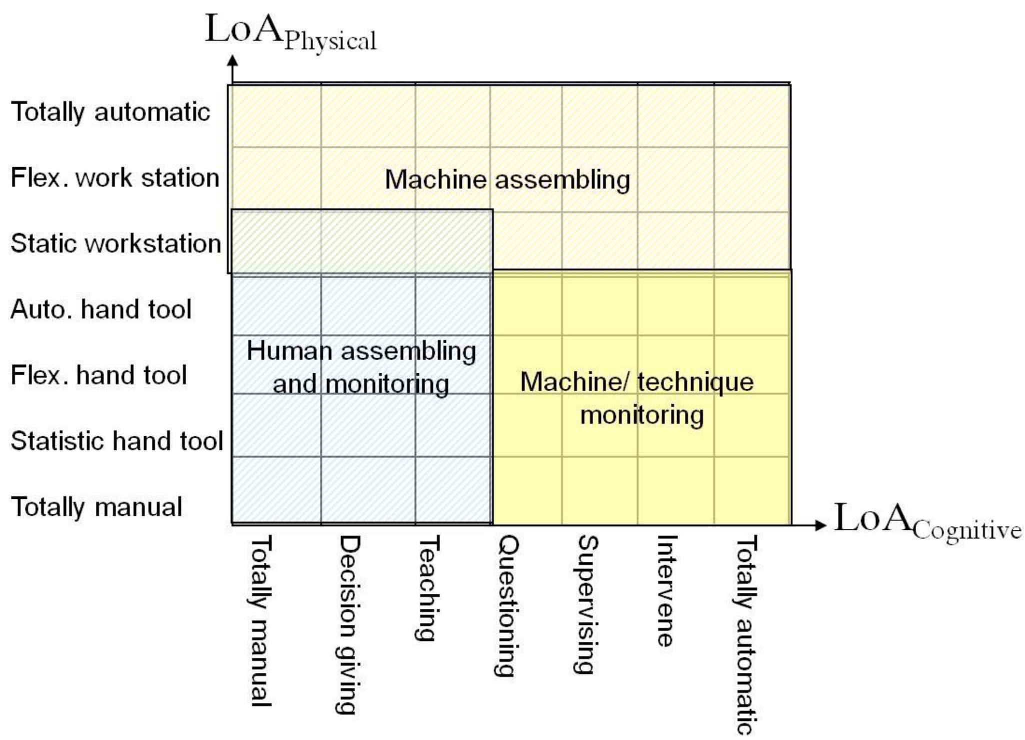


FIGURE 7 MATRIX ILLUSTRATING PHYSICAL AND COGNITIVE LEVELS OF AUTOMATION (LOA)

The matrix is used as a quantitative way of measuring the current LoA in the chosen areas´ tasks. The result is used for further analysis to meet triggers for change and also to make the company understand their mind set in a clearer and more objective way when it comes to automation.

4.1.2 Paper 4[2]

This paper reviews ten methods or models developed during the last twenty years used for redesign, measuring or analysing a production system (further information about the different methods and models is to be found in Frame of reference). Furthermore, a comparison is done between the methods and models based on four focus areas, seen in table 6. The comparison is done with the aim of putting the developed DYNAMO++ and concept model into perspective due to the other methods and models. A literature study is used in order to review the methods and the focus areas.

TABLE 6 SUMMARY OF THE ASSESSMENT METHODS AND FOCUS AREAS

Assessment methods	Focus areas
DYNAMO++ (Fasth, et al., 2010) and Concept model (Fasth and Stahre, 2010)	1. What assessment scale and level of change within the production system is the main focus?
TUTKA production assessment tool (Koho, 2010)	2. Assessment objectives i.e. what is the methods' main measurement parameters?
Systematic Production Analysis (SPA) (Ståhl, 2007)	3. Assessment methods i.e. qualitative or quantitative methods?
Productivity Potential Assessment (PPA) (Almström and Kinnander, 2007)	4. Where within the dimensions of Socio-Technical and Physical - Cognitive are the methodology's main focus?
Lean Customisation Rapid Assessment (LCRA) (Comstock, 2004)	
A model for types and levels of human interaction with automation (Parasuraman, et al., 2000)	
Complementary Analysis and Design of Production Tasks in Socio-technical Systems (KOMPASS) (Grote, 2004, Wäfler, et al., 1997)	
Cognitive Reliability and Error Analysis Method (CREAM) (Hollnagel, 1996, Hollnagel, 1998)	
Task Evaluation and analysis Methodology (TEAM) (Johansson, 1994, Wäfler, et al., 1997)	
Taxonomy for Cognitive Work Analysis (Rasmussen, et al., 1990)	

The selection of methods is always hard to do but in this case the author chose methods related to national and international well-known and well-cited developers.

Focus area 1 has been chosen to be able to determine if the models or methods should or could be used in a design phase or in a running phase of the system, i.e. large or minor changes. Furthermore, if the methods had a strategic and organizational approach or a "shop-floor" approach.
Results show that all of the methods had a shop floor approach. This resulted in an empty quadrant in the evaluation matrix (Socio-Physical), in focus area 4.

Focus area 2 has been conducted in order to determine if the method is primarily investigating cost and/or productivity issues or if the methods are investigating other effects as well.

[2] FASTH, Å. (Accepted for publication) REVIEWING METHODS FOR ANALYSING TASK ALLOCATION IN A PRODUCTION SYSTEM *International journal of logistic management*.

To illustrate the results from focus area 3 and 4 a matrix were developed with two axes. The first axis' dimensions are Socio and Technical and the dimensions of the other axis are Physical and Cognitive. This forms four areas in which the methods and models could be placed.

Focus area 3 are aiming to investigate if the more quantitative methods is placed in the technical-part quadrant and the more qualitative methods are place in the socio-part of the system.

Focus area 2 and 3 are closely connected to each other. If the method is focused on cost and productivity it is defined as quantitative and is grouped in quadrant Technical-physical. If the methods are more focused on cognitive behaviour and sociological aspects they are usually qualitative and grouped in the Socio-cognitive quadrant.
The Socio-Physical quadrant has a more organisational approach and the Technical-Cognitive quadrant is treating artificial intelligence and autonomous systems. None of the methods were place in these quadrants.

Focus area 4 is a result of the first three focus areas and resulted in a matrix illustrated in Figure 8 where the ten assessment methods are placed due to results from the earlier focus areas and the definitions of the quadrants. The aim is to determine how the methods are handling the issue of assess task allocation and Levels of automation in their models.

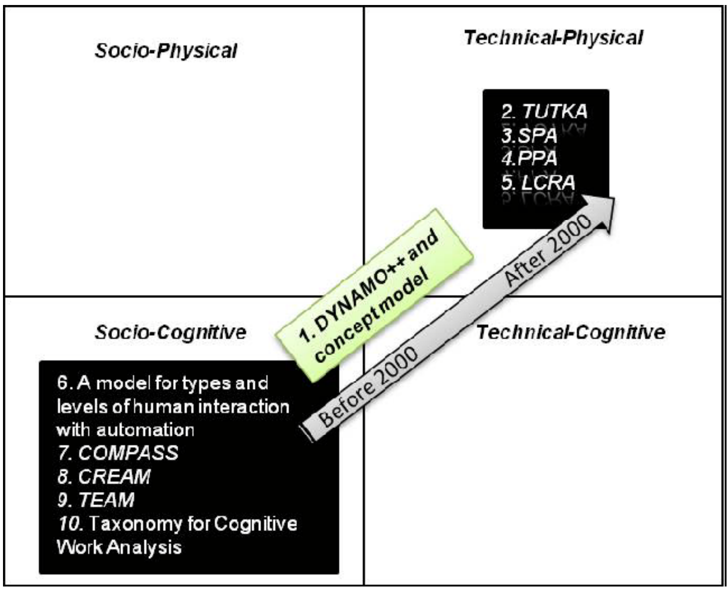


FIGURE 8 RESULT OF THE METHOD REVIEW (FASTH, ACCEPTED FOR PUBLICATION)

Results show that the methods conducted before the year of 2000 had a clear Socio-cognitive and qualitative approach while the method conducted after the year of 2000 had a more Technical-physical and quantitative approach towards the issue of automation and resource and task allocation in the system. Only DYNAMO++ had the main focus on measuring and assesses Levels of automation.

The result shows that the DYNAMO++ and the Concept model is in-between the socio-cognitive models and the technical-physical models when measuring and analysing a production system. The model takes into consideration both physical and cognitive Levels of Automation in a more delicate scale than the other methods and models which makes the task allocation measurements and analysis more precise. Furthermore, the model also considers the social aspects in terms of competence within the operator group and the information flow to and from the cell or station.

4.2 RESULTS RELATED TO RQ 2

The sections below will give a short description of the most important results in the papers related to

RQ2: ***How should LoA be measured and analysed in assembly systems?***

This research question will explain the evolution of finding an easy-to-use methodology for industry and a more logic concept model to enable data analysis, developed by the author for measuring and analysing LoA in assembly systems.

4.2.1 PAPER 2[3]

The aim of the second paper (Fasth, et al., 2008) was to present the further development of the DYNAMO methodology (Frohm, 2008) with focus on the analysis phase and its constituent steps. The methodologies used to write this paper were observations and semi-structured interviews and measures in the industrial case studies and literature study. A total of thirteen cases were analysed:

- Eight case studies [Two of the case studies within the ProAct project and six of the case from the DYNAMO project (Granell, et al., 2007)] were performed with the DYNAMO method.
- Five case studies were conducted to validate the developed methodology, DYNAMO++.

The DYNAMO method consists of eight steps. The developed method consists of twelve steps, divided into four phases. The skeleton of the DYNAMO method, i.e. the first six steps (with minor changes), is used as a base for the further development. The first two phases, i.e. pre-study and measurement, investigate the current state of the system e.g. product variants, number of components, number of operations and tasks within the chosen area, number of shifts and number of operators and levels of automation (LoA). Methods used are Value Stream Mapping (VSM), Hierarchic Task Analysis (HTA), structured interviews and the LoA taxonomy.

The major contribution of the further development of the method is within the analysis and the development of the implementation phase. One of the main developments in the analysis phase is the attempt to transform the reference scale, developed by Frohm (2008) into a more logical description of a matrix. Described in equations 1.1-1.3:

$1 \leq LoA_{total} \leq 49$ (Eq. 1.1)

$LoA_{total} \rightarrow (LoA_{mech}) \wedge (LoA_{info})$ (Eq. 1.2)

WHERE

$LoA_{mech}\,(y) = 1 \leq y \leq 7$ and $LoA_{info}\,(x) = 1 \leq x \leq 7$ (Eq. 1.3)

Eq 1.1 describes the number of possible solutions within the matrix (LoA_{total})

Eq 1.2 describes the relation between LoA_{mech} (later $LoA_{physical}$) and LoA_{info} (later $LoA_{cognitive}$)

Eq. 1.3 defines the discrete steps at each axis

The equations were formulated to get a logical ground and to be able to add dimensions or parameters to the methodology. This matrix is used to visualise the different levels of automation. It is also used in the analysis phase to show the results of the measurements and the suggestions of possible improvements.

[3] Fasth, Å., Stahre, J. and Dencker, K. (2008) Measuring and analyzing Levels of Automation in an assembly system. *Proceedings of the 41st CIRP International Conference on Manufacturing Systems (ICMS),* Tokyo, Japan.

Furthermore a square within the LoA matrix was developed in order to simplify and visualise the result of the analysis step. The Square of Possible Improvements (SoPI) illustrates the span within the matrix by which the companies believe their systems could be improved, in terms of different parameters, resources and demands. The logic behind SoPI is illustrated in equations 2.1-2.6:

$SoPI \rightarrow (LoA_{mech}\ (min; max)) \wedge (LoA_{info}\ (min; max))$ (Eq. 2.1)

$SoPI = LoA_{mech}\ (min; max) * LoA_{info}\ (min; max)$ (Eq. 2.2)

WHERE

$LoA_{mech}\ (y) = 1 \leq min \leq max \leq 7 \wedge LoA_{info}\ (x) = 1 \leq min < max \leq 7$ (Eq. 2.3)

$SoPI_{task} \leq LoA_{total}$ (Eq. 2.4)

$SoPI_{task} \subseteq LoA_{total}$ (Eq. 2.5)

Eq 2.1 defines the relation between the SoPI and the axis

Eq 2.2 defines the square itself

Eq. 2.3 defines the discrete steps within the square

Eq 2.4 defines that the square itself should have less or equal number of solutions than the matrix

Eq. 2.5 defines that the solutions of the SoPI should be e part of the solutions within the matrix.

In order to prevent sub-optimisation from task to operation optimisation, one condition regarding this was developed. In order to perform an operation optimisation, all the $SoPI_{task}$ has to be represented in the $SoPI_{operation}$ in order to make an optimisation (Eq. 2.6); if not, one solution is to do an optimisation with some of the tasks and do a task optimisation on the others. It could be described as:

IFF $SoPI_{operation} \subseteq \sum_{task=1}^{n} SoPI_{task}$, THEN operation optimisation is possible (Eq. 2.6)

The Square of Possible Improvements (SoPI) indicates the span within the matrix where company personnel believe their systems could be improved. The improvement potential is seen from different perspectives described by parameters, resources and demands. It is important to state that the information from the current state analysis is used as input for the future state solutions. The development of extended method logic and the addition of the time dimension to the existing LoA reference scales will make it easier to simulate different assembly system solutions. Moreover, it will provide a measurable value that can be used for comparing the present and future assembly system. This would provide companies with a deep foundation for decision making in the planning and implementation phases of their future assembly system. Focus on time parameters and follow-up would facilitate measurement of the change from the old to the new current stage. Moreover, it would provide a measurable value with which comparisons between the present and future assembly systems is made possible.

4.2.2 PAPER 3[4]

The aim of this paper was to investigate if there were relations between the parameters time, flexibility and LoA. Three questions were discussed:

- Time and/or Flexibility has been important in the latest paradigm shifts; is it still important today?
- Does Levels of Automation need to be changed to achieve time savings and/or increase flexibility in today's assembly systems?
- Could Lean tools like JIT simplify the understanding about Levels of Automation, flexibility and time savings?

In order to answer these questions six case studies were conducted using the DYNAMO++ methodology illustrated in Figure 9.

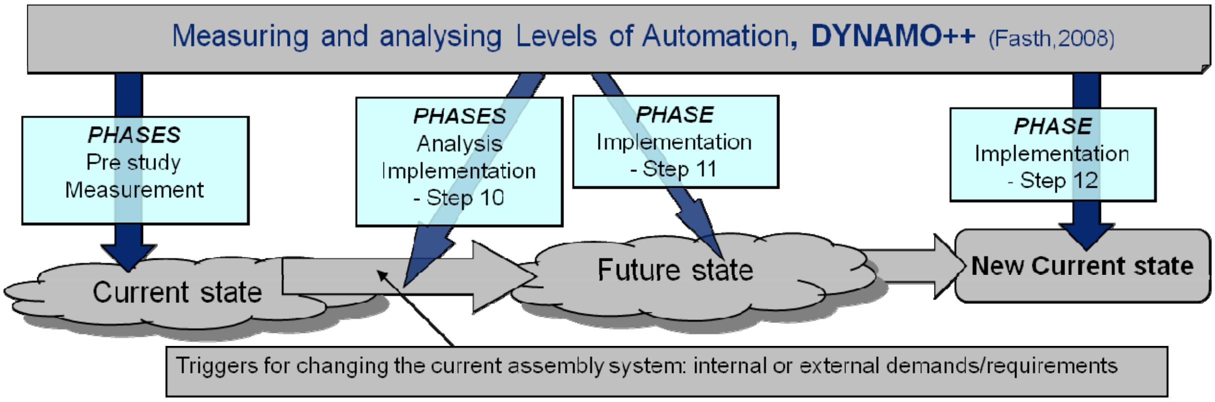


FIGURE 9 AN OVERVIEW OF THE 4 PHASES IN THE DYNAMO ++ METHODOLOGY (FASTH AND STAHRE, 2008)

In the current state, data were gathered about flow, type of assembling and number of products in the measured area. Flow and time parameters were also documented. A measurement of the current state's Level of Automation was carried out; the value is based on the automation level that the operator used to perform the task. The result of the current state phase is illustrated in Table 7.

TABLE 7 CURRENT STATE IN SIX CASE STUDIES

Current stage	Company A	Company B	Company C	Company D	Company E	Company F
Production area	Engine parts	Chemistry [28]	Electronics	Cooling modules [29]	Trucks	Vessels [30]
Type of flow	U-cell	Line	U-cell	Job Shop	Line	U-cell
Type of Assembling	ATO	ATS	ATO	ATS	ATO	ATO
Type Assembling	Batch	Batch	One piece flow	Accord based	One piece flow	Batch
Number of Products	2 main 30 variants	2 main	2 main	3 main	3 main Costume made	4 main 8 variants
Number of Stations	4	9	5	8	5	9
Average $LoA_{Information (Used)}$	1	5	3	1	3	1
Average $LoA_{mechanical (Used)}$	1	5	5	1	-	1

ATO – Assemble-To-Order
ATS – Assemble-To-Stock

[4] **Fasth, Å.**, and Stahre, J., Does Levels of Automation need to be changed in an assembly system? - A case study, *Proceedings of the 2nd Swedish Production Symposium (SPS), Stockholm, Sweden, 2008.*

Results from interviews regarding the companies' trigger for change (illustrated in Table 8) show that Flexibility, *e.g. Volume and product*, and Time, *e.g. through-put time*, still are important factors for the companies to consider when redesigning their systems.

TABLE 8 TRIGGERS FOR CHANGE AND LEAN AWARENESS

	Company A	Company B	Company C	Company D	Company E	Company F
Triggers for change	Increase quality (Increase Cognitive LoA)	Decrease throughput time	Volume and product flexibility	Wants to buy a robot (increase mechanical LoA)	Simplify the information flow to the operators	Increase volume and product flexibility, visualise the flow
Lean Awareness (use of JIT tools [11])	Middle	None	High	None	Middle	Middle

High – The message had reached the operators and almost all the tools were implemented
Middle – Started with the early-on tools [11], the implementation had stopped at the white-collar worker level
None – have almost not heard of Lean Production

As a part of the analysis work, LoAs were measured and a SoPI was illustrated based on the logic from paper 2. Figure 10 illustrates an example from case study A, where the left matrix is an example of a task allocation for task 1.1 and the right matrix is an example of a possible operation optimisation between task 1.1-1.5. The matrix shows how the possible solutions decreases when going from a single task optimisation (18 possible solution) to a operation optimisation (6 possible solutions)

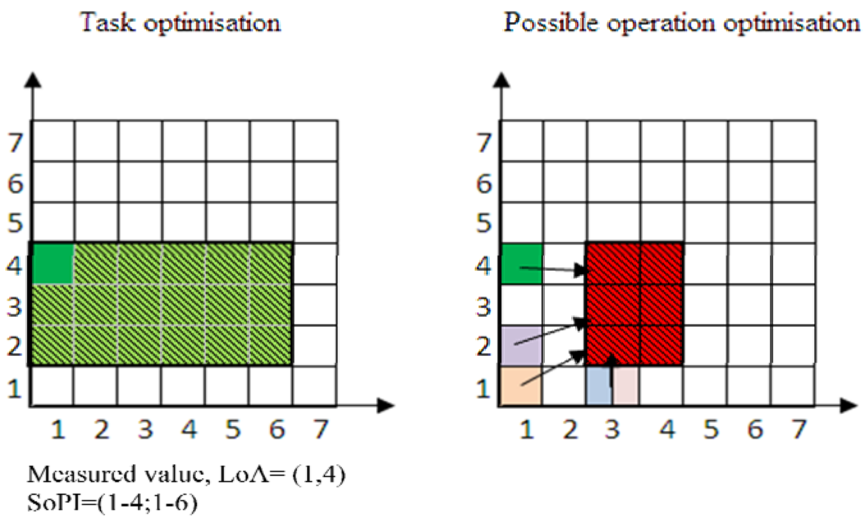


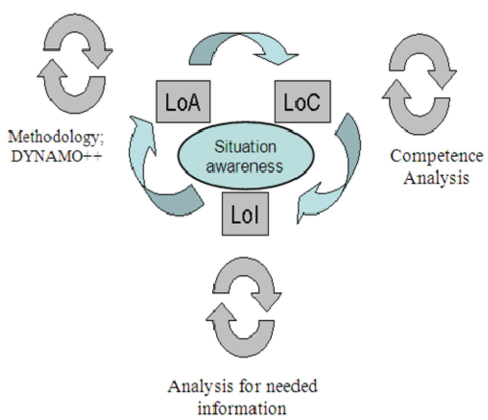
FIGURE 10 TASK AND POSSIBLE OPERATION OPTIMISATION

Results show that either the mechanical or information LoA needed to be changed in almost all companies in order to reach their triggers for change; $\text{LoA}_{\text{information}}$ (50 % of the companies) in terms of digital assembly instructions in different levels due to the operators' competence and experience, or visualisation of the production in terms of state lamps. $\text{LoA}_{\text{mechanical}}$ (33 % of the companies) in terms of conveyers (transport automation), and variable automation in terms of redundancy or plug-and-play flows. The degree of Lean awareness also seemed to have an impact on how these three parameters were treated. The companies with middle or high lean awareness found it easier to understand the DYNAMO++ methodology and the term Levels of Automation. Further, it was easier for them to understand time savings in terms of non-valuable time.

4.2.3 PAPER 5[5]

The aim of this paper was to describe a Meta methodology (the ProAct loop), for designing a proactive system in a structured way considering Automation (LoA), Competence (LoC) and Information (LoI), aiming to increase flexibility, achieve time minimization and increase the operators' action space. The effect of investigating the three areas is discussed in RQ3.

It is important to consider both the qualitative and quantitative aspects when redesigning an assembly system. The socio-technical school [42, 43] could be seen as an alternative in order to expand the operator action space and to find the interaction between the three areas, i.e. automation, competence and information. The "social system "could be related to the operators' roles, Level of Competence (LoC), Level of Information (LoI) and the cognitive Level of Automation (LoA). The technical system could be connected to mechanical LoA and in some cases LoI in terms of technical solutions (information carriers). The ProAct-loop, shown in figure 11 (illustration to the left), is a Meta methodology connecting the three areas by combining theory and methods. The loop is used in two iterations, the current stage mapping and the future stage analysis. The methodology was tested and validated in five Swedish production companies in 2007 and 2008.



Areas Levels	LoA cognitive	LoA physical	LoC	LoI
1	Totally manual	Totally manual	Skill based	Insufficient
2	Decision giving	Statistic hand tool	Role based	Sufficient for expert operator
3	Teaching	Flexible hand tool	Knowledge based	Sufficient for novice operator
4	Questioning	Automatic hand tool		Too much
5	Supervising	Static workstation		
6	Intervene	Flexible work station		
7	Totally automatic	Totally automatic		

FIGURE 11 METHODOLOGIES USED IN THE PROACT LOOP AND THE DIFFERENT LEVELS OF MEASUREMENT

In order to make a first statement about the system and its proactive potential, an attempt to quantify the three areas were done, illustrated in Figure 11 (illustration to the right). Through a deep understanding of the interaction and relation between the three areas, companies can avoid over- or under-automated systems. Also, excessive information and incorrect competence levels can be avoided. Further, companies will be able to balance the three areas and do changes where it is most needed. For example, low competence level can to some extent be compensated by higher levels in the information and/or automation area and vice versa. The operators' situation awareness will improve, thus increasing their ability to act proactively.

[5] **FASTH, Å.**, BRUCH, J., DENCKER, K., STAHRE, J., MÅRTENSSON, L. & LUNDHOLM, T. (2010) Designing proactive assembly systems (ProAct) - Criteria and interaction between automation, information, and competence *Asian International Journal of Science and Technology in production and manufacturing engineering (AIJSTPME),* 2 (4)**,** 1-13

4.2.4 PAPER 1[6]

The aim of this paper was to describe a concept model containing a main loop for measuring and analysing LoA, illustrated in Figure 12. Furthermore, the concept model aims at mapping other areas that are important to consider when doing a task allocation between resources. The concept model is a further development and a leaner version of the ProAct methodology presented in P_5. The concept model is aiming at determining appropriate task allocation with a span of various levels of automation in assembly operations.

Methods used in this paper are empirical collections, i.e. interviews and measures and a theoretical framework. The concept model was first presented in a proceeding at the *3rd CIRP Conference on Assembly Technologies and Systems*[7].

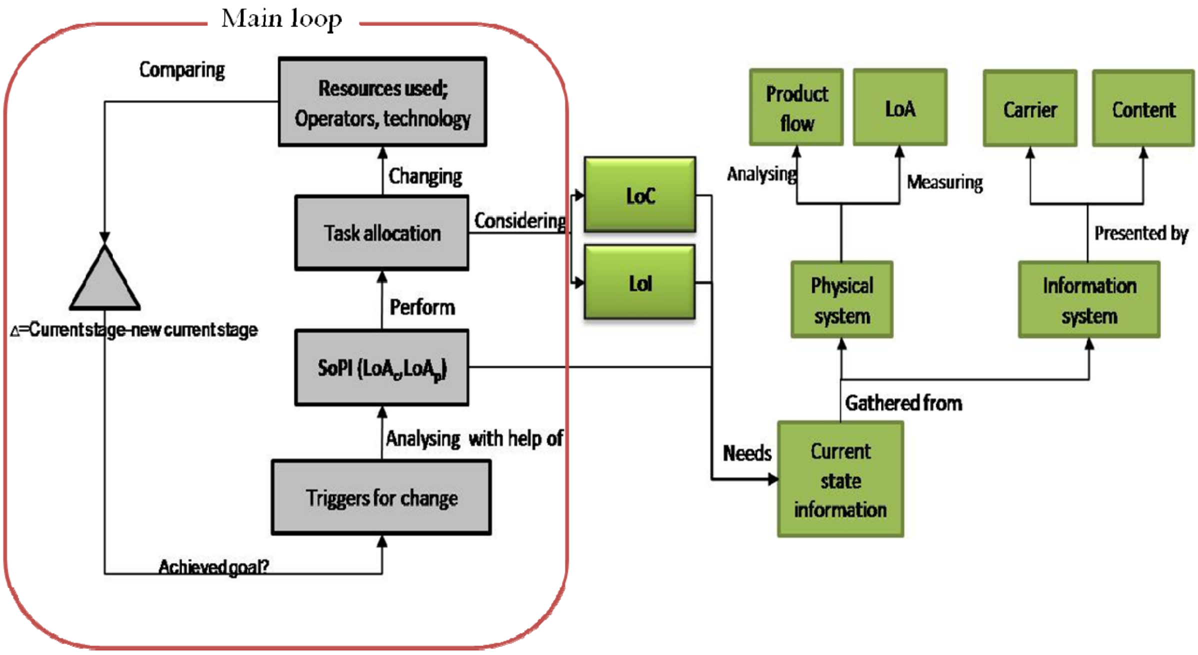


FIGURE 12 CONCEPT MODEL, FURTHER DEVELOPED FROM DYNAMO++ (FASTH AND STAHRE, 2010)

The model contains two parts. The first part is the main loop which has its base in the 12-step methodology of DYNAMO++, described in paper 2. The second part is describing the other parameters that are important to consider when re-designing an assembly system. Both parts are related to the ProAct loop presented in paper 4.

The results from this paper are an attempt to describe the underlying methodologies in a more visual and leaner way. Furthermore, the concept model is an attempt towards a more logical explanation in order to develop a future ontology.

[6] **FASTH, Å**. & STAHRE, J. (2nd Review) Task allocation in assembly systems -Measuring and analysing Levels of Automation, *Special issue (Theoretical Issues in Ergonomic Science)*

[7] **FASTH, Å**. & STAHRE, J. (2010) Concept model towards optimising Levels of Automation (LoA) in assembly systems. *Proceedings of the 3rd CIRP Conference on Assembly Technologies and Systems,* Trondheim, Norway

4.3 RESULTS RELATED TO RQ 3

The sections below will give a short description of the most important results in the papers related to:

RQ3: What are the expected effects when analysing and changing LoA?

Cost is a common parameter that is often used when improving production systems. This research question will discuss whether there are other parameters that are linked to LoA and could get as good or better results than just focusing on cost when deciding if the level of automation should be changed.

4.3.1 PAPER 1[8]

Results from Paper 1 show that it is possible to compare two different levels of automation and to use them as alternatives in order to create flexibility in the system (volume and route). The results are illustrated through a case study. Part of the results has also been published (Fasth, et al., 2008)and (Fasth and Stahre, 2008). The first two phases in the DYNAMO++ were used for a current state analysis. The company's trigger for change was to increase volume flexibility for a specific product family. In order to analyse if this was achievable an illustration of the product flow and an investigation of the bottleneck was done. The company had integrated redundancy in the bottleneck station, as illustrated in Figure 13. The matrix shows two different alternatives that were used for assembling. Alternative 1, the main path, is a robot cell, LoA= (6; 5). The second alternative is a station with an operator and a fixture, LoA= (5; 3). This solution was used as an alternative when the robot cell was unusable. In order to fulfil the enhancement of volume flexibility, a solution is to use both stations and to perform task allocation, i.e. dynamically changeable LoA depending on the order status on a daily basis.

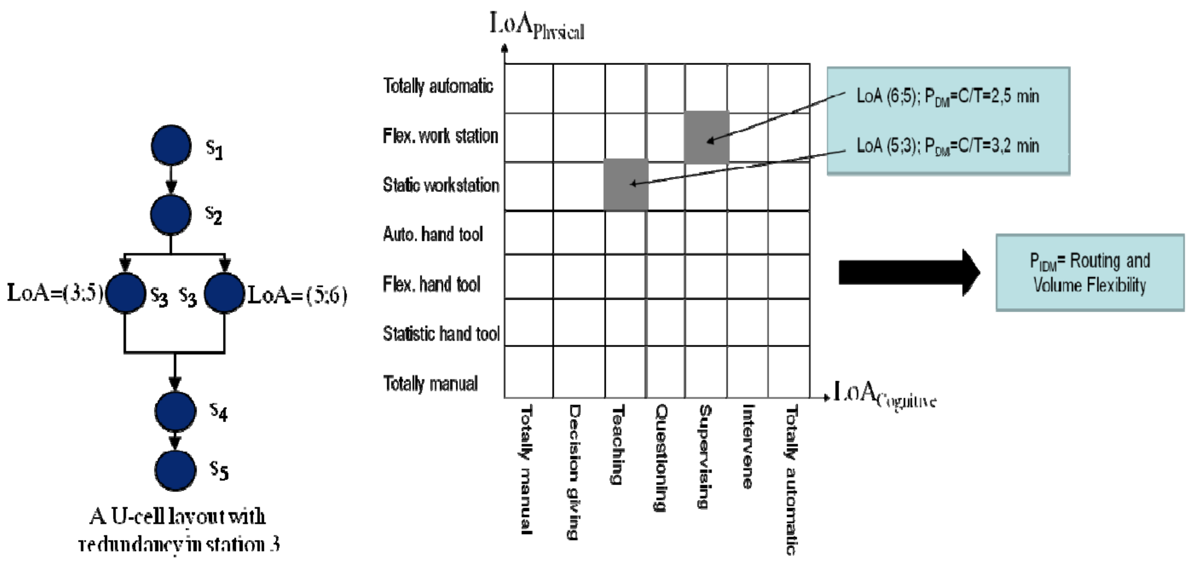


FIGURE 13 OBSERVED LOA AND CYCLE TIME (C/T) VALUE FOR STATION 3 (S3)

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[8] **FASTH, Å**. & STAHRE, J. (2nd Review) Task allocation in assembly systems -Measuring and analysing Levels of Automation, *Special issue (Theoretical Issues in Ergonomic Science)*

The result of this task allocation gave four alternatives to elaborate regarding volume and route flexibility.

> The robot cell is used as the main resource in the system. The productivity for one normal day is 24 products per hour, i.e. 192 products per shift. Assume that a breakdown for two hours happens on the robot cell. Without the routing flexibility the loss will be 24 parts per hour = 48 products. With the routing flexibility the company is able to use the static work station under the reparation producing 18 products per hour, i.e. a loss of 5 products per hour = 10 products.

The four alternatives give a variance of 144 products (min 152, max 296).

The amount of products produced with different alternatives is shown in Figure 14.

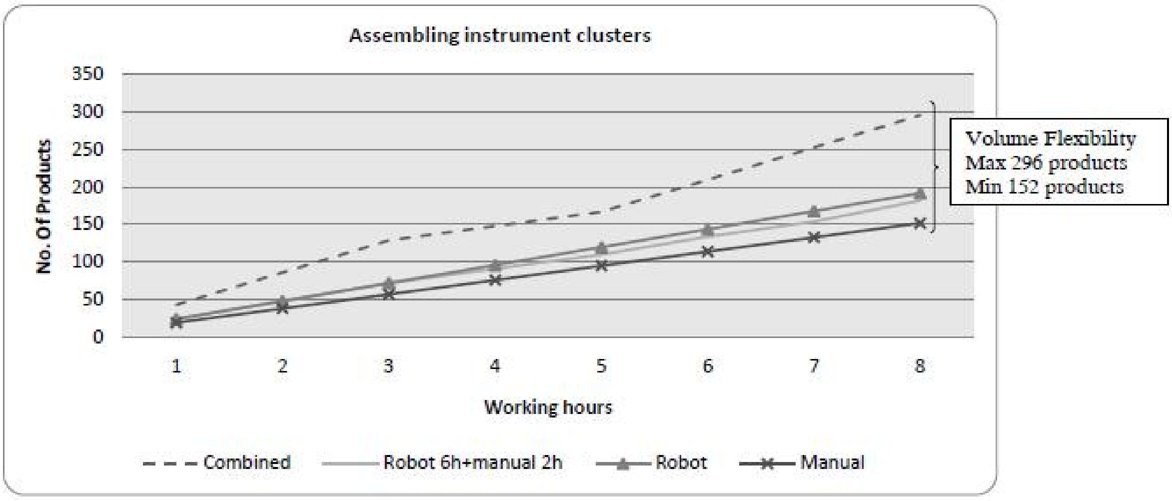


FIGURE 14 CREATING VOLUME FLEXIBILITY THROUGH TASK ALLOCATION

This case shows how task allocation and changing recourses could be illustrated in an easy way for the company so that it can take well-founded decisions due to the volume it wants to produce.

4.3.2 Paper 5[9]

The results in this paper related to RQ3 are to investigate the criteria and interaction between three areas: automation, information, and competence in order to design a proactive assembly system. The methods used to achieve this were the DYNAMO++ methodology, definition of operators' roles and work tasks(Sheridan, 1995, Stahre, 1995) and the Skill-Role-Knowledge(SRK)-model (Mårtensson and Stahre, 2003, Rasmussen, 1983) . Through a deep understanding of this interaction, an optimising of the separate areas in a structured way using the proposed Meta-method (the ProAct-loop, described under RQ2) could be done. As a result, companies will be able to balance the three areas and optimise where it is most needed. One example is the short-time planning and the ability to adapt to for example increased need for more products, or the need for another machine when the main one is done, i.e. volume and route flexibility shown in the previous example from Paper 1. Further, a low competence level can to some extent be compensated by higher levels of information and/or through higher cognitive LoA and vice versa. The square within the LoA matrix (Fig. 15) represents the tasks or operation's action space in which automation solutions for the future assembly system may vary. Depending on how movement in this square is done, the effort to change to other technical solutions, is reflected on both the level of information and the level of competence.

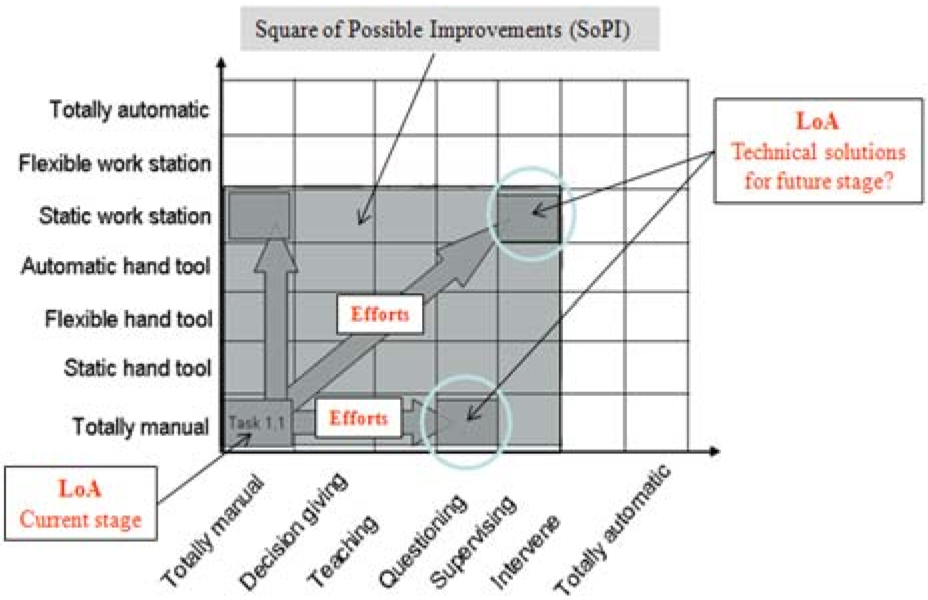


FIGURE 15 EFFORT NEEDED TO CHANGE LOA WITHIN A SYSTEM

In proactive assembly systems, operators are encouraged to take more responsibility, far beyond managing operation and disturbances. Requirements on frequent reconfiguration, either initiated by explicit demands, or by changes due to proactively foreseeable problems or requirements, are normal. This means that in the future there is a need to take operator abilities and limitations into consideration, as well as the operators' various ways of using information and making decisions in different working situations (Dencker, et al., 2007).

[9] **Fasth, Å**., Bruch, J., Dencker, K., Stahre, J., Mårtensson, L. and Lundholm, T. (2010) Designing proactive assembly systems (ProAct) - Criteria and interaction between automation, information and competence, *Asian International Journal of Science and Technology in production and manufacturing engineering (AIJSTPME), vol 2 issue 4, pp.1-13*

4.3.3 PAPER 6[10]

The aim of this paper is to investigate if cognitive automation can be used to increase quality in a complex final assembly context. An industrial case study has been executed to test if *there is a relation between cognitive automation, quality and quantitative (objective) station complexity,* illustrated in Figure 16.

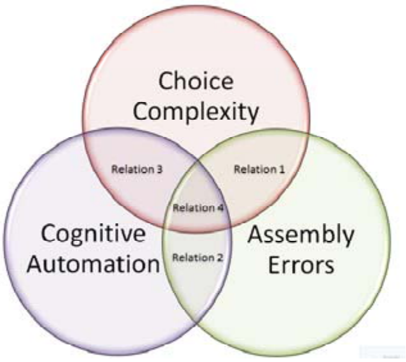


FIGURE 16 THE INVESTIGATED RELATIONS

The increased task complexity in assembly needs to be handled; otherwise the quality of the product and productivity in the system could be affected. In order to maintain high quality and reduce the complexity, one solution could be to consider cognitive automation for the operator, e.g. technical support to know how and what to assemble and to be in situation control. An industrial case study has been executed in order to investigate the effects cognitive automation have on quality, in terms of assembly errors, in a complex final assembly context.

In order to test the aim of the paper, an area of interest was selected. The area is one of the most complicated in the final assembly with a very high product variety and a large number of parts. The chosen area consists of a total number of sixteen stations where seven have been studied within this project (the grey operators in Figure 17 represent the chosen stations). The chosen stations are a part of the pre-assembly area for the preparation line of engines. In the line the engines are customised with correct driveshaft, cables etc. The engines assembled are used in all models and variants on the main assembly line. There are two areas for the pre-assembly of the engines and this is the second area, Power Pack 2 (PP2).

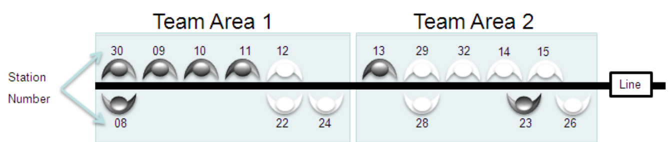


FIGURE 17 THE SELECTED AREA WITH TOTAL NUMBER OF STATIONS AND SELECTED STATIONS

Measuring Levels of Automation (LoA) was made from direct observations and from standardised assembly instructions. An advantage of the use of two sources of information is that the standardised assembly instruction does not always correspond with the reality which we want to capture.

[10] Fässberg,T., **Fasth, Å**., Hellman, F., Davidsson, A., and Stahre, J (accepted for publication), Interactions between complexity, quality and cognitive automation, *Proceedings of 4th CIRP Conference On Assembly Technology Systems*

Two models were assessed for each station, the most common model regarding demand and the heaviest model to produce regarding time. The distributions of the tasks for the two models are presented in the matrix illustrated in Figure 18.

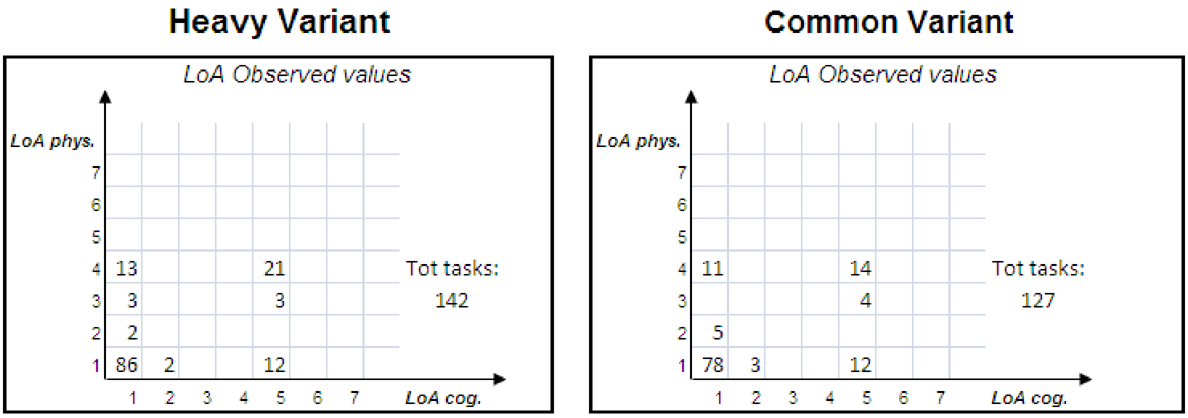


FIGURE 18 LOA MEASUREMENT FOR ALL THE SEVEN STATIONS

By looking at the results, it is clear that the majority of the cognitive support is either none, LoA_c=1, or very high, LoA_c=5. Results show that 62 percent (H) and 64 percent (C) were made with LoA level= (1; 1), i.e. by hand and with own experience. The fact that so many tasks are done without cognitive support could have an impact on quality. Further, 25 percent (H) and 24 percent (C) is done with LoA_{cog} =5 (often pick-by-light or indicators of what bit to use for the pneumatic screwdrivers).

This paper shows that it is possible to use quantitative measures in order to show relations between station complexity, quality and cognitive automation. These methods could be further used in order to improve both the resource efficiency and resource allocation in order to get an effective assembly system. Then, the operators' competence and experience should also be taken into consideration, which is not fully covered by using the three methods. The main conclusion is that there is evidence that cognitive support is needed in final assembly to minimize the negative effects of complexity.

5 DISCUSSION

This chapter will discuss the most important results in the appended papers connected to the research questions; this will be done in relation to four areas of theoretical and practical contribution. Further, a discussion regarding choice of methods will be done. Lastly, a discussion of future work will be addressed.

According to (Wiendahl, et al., 2007), on assembly level, an enabler to achieve flexible and changeability systems is the ability to upgrade or downgrade the degree of automation. For assembly operations, in contrast to machining operations, there is often the possibility to perform them either manually or automatically. Earlier research (Dekker and Woods, 2002, Parasuraman and Riley, 1997, Sheridan, 1995) show that in order to make well founded decisions, automation has to be seen as different levels of automation. Furthermore the automation decisions must have a well-founded ground and be a part of the company's strategy plan (Säfsten, et al., 2007). Inagaki (Inagaki, 2003) argues that in order to analyse the choice of automation with regard to cost and benefit, quantitative models are needed. Further, he lists the main arguments regarding the choice of automation and the need for quantitative methods in order to make a well-structured decision:

1. Without a quantitative model, it is not possible to evaluate tradeoffs between cost and benefit.
2. Intuition is not powerful enough to analyze time-dependent characteristics of cost and benefit in a dynamically changeable situation.
3. Robustness or sensitivity of solution (whether to automate or not) can be analysed only when quantitative models are available.
4. Suppose a current plan is to ''automate'' a specific function. With a quantitative model, we can investigate to what extent the plan is superior to an alternative that leaves the function under manual control.

By quantifying means it is possible to compare some kind of data with each other in a statistical way (Miles and Huberman, 1994). In line with Inagaki, Older et al. (Older, et al., 1997) stated the need for a more easy-to-use quantitative method for analysing Levels of Automation with their seventeen requirements. Results from the appended papers show that automation can be used as a primary parameter in order to analyse assembly systems in relation to competence, information, quality, time and flexibility. Furthermore, the results show the importance of having more than two levels of automation and to also in count the cognitive automation when searching for possible solutions in order to get a more levelled and precise automation solution.

Therefore the aim of this thesis, *quantifying, measuring and analysing the physical and cognitive Levels of Automation to enable competitive assembly systems,* is of relevance and will be further discussed in this chapter.
Therefore the aim of this thesis; *quantifying, measuring and analysing the physical and cognitive Levels of Automation to enable competitive assembly systems* is of relevance and will be further discussed in this chapter.

5.1 SUMMARY OF THE APPENDED PAPERS RELATED TO THE RQS

Below follows a short summary of the appended paper with regard to each RQ.

5.1.1 WHY IS IT IMPORTANT TO QUANTIFY LEVELS OF AUTOMATION (LOA) IN AN ASSEMBLY SYSTEM CONTEXT?

Summary of the results from appended paper 1 and 3 related to RQ1: Results from the appended papers (1 and 3) show that it is important to consider LoA as a quantitative measure in order to be able to compare with other parameters important for the company (connected to RQ3): "talk to farmers in farmers' way". Further to be able to go from a more socio-soft way of thinking of primarily cognitive automation, towards a more technical explanation. The conducted case studies show that the cognitive automation is often forgotten or not prioritised. In order to increase competitiveness and to survive in a more complex environment, cognitive automation needs to be considered and developed further. Moreover, the case studies showed that the ways the automations were chosen were based on experience and "common sense" which is not always optimal; this shows a need for a structured way of measuring and analysing LoA in order to chose solutions in a more structured way (RQ2).

5.1.2 HOW SHOULD LOA BE MEASURED AND ANALYSED IN ASSEMBLY SYSTEMS?

Summary of the appended papers 1,2 and 4 related to RQ2: Results from papers 1, 2 and 4 show that it is important to create a method that involves both the socio-cognitive (Qualitative) and the technical-physical (Quantitative) part when redesigning an assembly system: current state analyses to collect data about LoA, maturity in LEAN and system parameters (number of products, variants, type of layout etc.), measurement of LoA (both cognitive and physical), analysis due to triggers for change (relate to RQ3), implementation and follow-up.

5.1.3 WHAT ARE THE EXPECTED EFFECTS OF ANALYSING AND CHANGING LOA?

Summary of the results, i.e. RA3: According to papers 1, 4, 5 it is important to investigate the triggers for change within a company before redesigning the system. The next step will be to determine how to achieve this change. This has to be done in a structured way as discussed in RQ2. The most expected and obvious change might not be the most optimal. According to several case studies (Fasth, et al., 2011, Fasth and Stahre, 2008) the most common triggers beside decreasing cost are: increase (volume and route) flexibility, increase proactivity, decrease or manage complexity and decrease cycle time. The prime focus with this RQ is to determine if a change of mindset, from looking primarily at cost to also consider pros and cons with different LoAs and other parameters related to both LoA and cost, could be a part of being more competitive.

5.2 Contribution matrix

The further discussion will be based on the contribution matrix, brought up in Chapter 2, p.11. The quadrants have been filled in with the contributions from the appended papers (RA) (illustrated in Figure 19) and will be discussed based on the four areas in the theoretical framework in chapter 3 and the results from the appended papers listed in Chapter 4.

	Scientific	Industrial
Theoretical	RA1: Development of LoA matrix, illustration of a quantitative tool. Definition of LoA	RA2: Validation of DYNAMO++ and the concept model
Practical	RA2: Development of DYNAMO++ and the concept model	RA3: Use of DYNAMO++ and the concept model. Shown effects of measuring and analyzing LoA

FIGURE 19 RELATIONS BETWEEN THE THEORETICAL AND PRACTICAL CONTRIBUTION FROM A SCIENTIFIC AND INDUSTRIAL PERSPECTIVE

5.2.1 Practical contribution from a scientific perspective

This section will discuss the practical contribution with the results from the appended papers related to RQ2 and in relation to the theoretical framework of assessment methods

(RA2: Development of DYNAMO++ and the concept model)

Without a quantitative model, it is not possible to evaluate tradeoffs between cost and benefit of different levels of automation (Inagaki, 2003). According to (Säfsten, et al., 2007) it has proved to be more successful to formulate an automation decision in congruence within the company rather than having automation as an only concern to reduce cost, i.e. the automation decision is pushed on the organisation (Boyer et al., 1996; Winroth et al., 2007). Results from papers 1, 4 and 5 show that considering LoA based solely on cost savings might not be the optimum solution. The quantitative approach and illustration of the LoA matrix could be used as a tool in order to analyse the current stage and to achieve the triggers for change and design a new current stage – even though results from paper 4 and 5 show that it is important to consider the more qualitative aspects such as Level of Competence and Level of Information when doing an in-depth study after the first analysis.

According to Older et al. requirements on a quantitative method are: "*new methods must be developed jointly with its users, i.e. adaptable to be put in practice (Older, et al., 1997, Waterson, et al., 2002) and the method must be validated within its planned area of use*". Existing models about the content and process of manufacturing strategy,(Skinner, 1969) deal with automation very briefly as a question that is included in the process technology decision (Säfsten, et al., 2007). Results from paper 3 show that the models or methods on "shop-floor" level are either focusing on the socio-cognitive of the system, i.e. competence, skill, operator group control/planning etc. or the more physical-technical part of the system, i.e. pre-defined criteria for a "perfect system", measurements and cost savings.

In line with Olsen (Olsen, 2004), the developed methods and model presented in papers 1, 2 and 4 are an attempt to combine qualitative (socio-cognitive) and quantitative (physical-technical) approaches rather than see contradictions between the two modes of analysis, and in line with Older et al, develop an easy-to-use method for the planned area of use, i.e. final assembly that could be used from shop-floor level up to a strategic level. The evolution of how to measure and analyse LoA presented in paper 1, 2, 3 and 5 are illustrated in Figure 20.

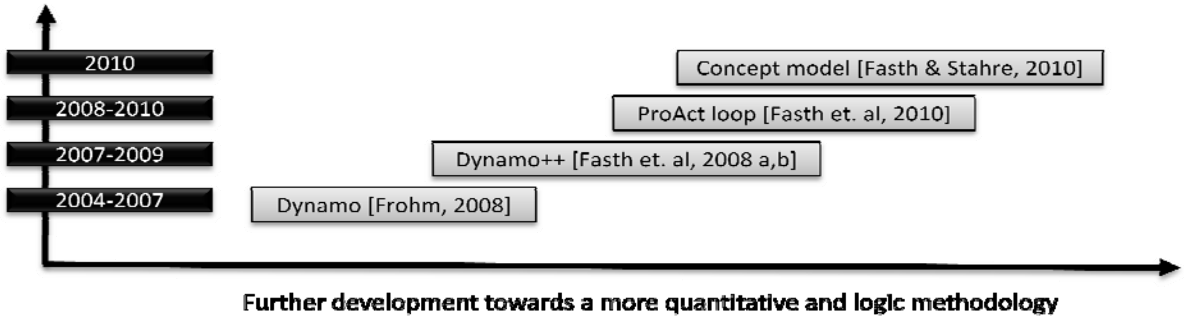


FIGURE 20 EVOLUTION FROM DYNAMO TO THE CONCEPT MODEL

Results from paper 2 and paper 3 describe the DYNAMO++ methodology which was developed in association with five case companies and further validated in six cases. The focus was to develop the LoA matrix and the analysis steps with regard to the logic within the matrix. According to Secondly, the ProAct loop was presented in paper 4. The loop or Meta model consisted of three methodologies, where DYNAMO++ was one of them. In the ProAct loop, the DYNAMO++ was more focused on quantifying LoA and related the measured and analysed industrial result to the other two areas (competence analysis and information mapping). The third and final evolution is the concept model, presented in paper 1, which is a lean version of the ProAct loop aiming towards a more logical mathematical model.

Is it possible to only use either one when it comes to quantitative and qualitative methods?

Two of the most obvious alternatives when developing a methodology or method are either to have a quantitative or qualitative approach. The two approaches have different pros and cons depending on in what context the method is going to be used. Of course there are extremists in this matter: *"There's no such thing as qualitative data. Everything is either 1 or 0"* (Kerlinger, 1960) and "*All research ultimately has a qualitative grounding*" (Campbell, December,1976). According to (Miles and Huberman, 1994) these two research approaches need each other more often than not. Results from paper 3 show a clear line between methods developed before and after the year 2000. The methods developed between 1990 and 2000 had a clear qualitative approach while the methods conducted between 2000 and 2010 had a clear quantitative approach. The aim of the concept model is to try to combine these two approaches into one model. Using quantitative methods is a way to fast-scan and get results on where the problem area is. Furthermore it is an easy way to compare different stations or cells with each other, statically. The qualitative methods could then be used for in-depth study of the issues. The thought with the concept model is to give the companies an easy overview of aspects or parameters to consider when redesigning a system. The main loop is aiming for a more quantitative approach. Results from paper 5 show that the quantitative approach within the concept model could be used as a first step to find relations between LoA, Complexity and quality. Then, the operators' competence (LoC, in Figure 24) and experience should also be taken into consideration, which is not fully covered by using only the quantitative methods. The areas are a mapping over areas to consider when automating an assembly system. These areas are a mix between qualitative and quantitative measures. By combining both quantitative and qualitative measurement approaches and combining different methods, the concept model could be used both as a fast scanning method to catch the problem areas and handle the triggers for change but also as an in-depth method.

5.2.2 THEORETICAL CONTRIBUTION FROM A SCIENTIFIC PERSPECTIVE

This section will discuss the theoretical contribution with the results in RQ1 in relation to the theoretical framework regarding Levels of Automation (LoA).

(RA1: Development of LoA matrix, illustration of a quantitative tool. Definition of LoA)

In order to be able to measure and analyse LoA, a quantifiable way of illustrating LoA has to be developed. To determine what to automate, a classical task allocation strategy from 1951 (the MABA-MABA list) was proposed by Fitts (Fitts, 1951). It was an attempt to suggest allocation of tasks between humans and machines by treating them as system resources, each with different capabilities. Two examples, i.e. "*M*achines *A*re *B*etter *A*t" performing repetitive and routine tasks while "*M*en *A*re *B*etter *A*t" improvising and using flexible procedures. At the time, comparing man and machine, was a revolutionary thought that caused a lot of debate. The questions are: is the list still is applicable in an assembly context and is the list quantitative enough?
A problem related to MABA-MABA-oriented methods is the simplicity, e.g. "*put your allocation problem into the method and the solution will emerge from the other end*" (Dekker and Woods, 2002). The methods do not readily explain the cognitive actions for how and when to intervene, nor do they describe how to switch from level to level. Many researchers after Fitts have argued whether it is impropriate or not to automate or to compare man and machines, and how to allocate the different tasks to man *or* machine:

> Jordan (Jordan, 1963) argued whether you could actually compare man and machine, and that the two should be seen as complementary rather than conflicting resources when designing a man-machine system. Sheridan (Sheridan, 1995) proposed to "allocate to the human the tasks best suited to humans and allocate to the automation the task best suited to it". Hancock (Hancock and Chignell, 1992) argues that it is only when both human and machine can do the same task that the question of task allocation becomes an issue.

These arguments are still not quantitative enough, in order to measure and analyse LoA. An attempt after Fitts to assess LoA was Prince in 1985 (Prince, 1985) who designed a decision matrix, partly in line with Fitts in that some tasks were better performed by machines and some better by humans. But interestingly Prince also defined a set of tasks where the same task could and should be performed both by humans and by machines. Further, when there is no single allocation, the different resources need support from each other, which is in line with Jordan's argument. Until today a lot of different "lists" and methods have been published. The relevance of a task allocation process is obvious, yet there is still lack of systematic methods and, more importantly, methods that can be applied to advanced technological systems (Older, et al., 1997)**.**

Older et al. (Older, et al., 1997) in 1997 (and 2002) compares eighteen different methods (developed 1965 and 1992).Seven of them contains *quantitative evaluations* but none of the methods are considering both cognitive and physical automation regarding task allocation. Results from publication 3 (Fasth, 2011) show that five of ten methods compared (developed between 1990 and 2010) have a quantitative approach, but only the DYNAMO++ method considers both cognitive and physical automation on a task level. Automation design is not an exact science, however; neither does it belong in the realm of the creative arts, with successful design dependent upon the vision and brilliance of individual creative designers (Parasuraman, et al., 2000). Without a quantitative model, it is not possible to evaluate tradeoffs between cost and benefit of different levels of automation (Inagaki, 2003). Attempts to describe different levels of automation between extremes, *from totally manual to totally automatic* have been done.

According to Parasuraman and Riley, automation can be characterized by a continuum of levels *rather than* as an all-or-none concept (Parasuraman and Riley, 1997). In line with Parasuraman and Riley, Frohm (Frohm, 2008) defines Levels of Automation as:

> *"The allocation of physical and cognitive tasks between humans and technology, described as a continuum ranging from totally manual to totally automatic"*

The question today is not *either* continuum ranging or *rather than*. Results from paper 1 and 3 show that both industry and assessment methods developed by academia still sometimes see automation (partially the physical) as a binary decision. The author believes the question that should be asked is how to quantify the levels so that a more logic approach could be made when measuring and analyzing LoA, i.e. *discrete steps* from totally manual to totally automatic. To be able to make it simple and in order to design a LoA matrix, Levels of Automation is defined as:

> *The allocation of physical and cognitive tasks between resources (humans or technology), described as discrete steps from 1 (totally manual) to 7 (totally automatic), forming a 7x7 LoA matrix containing* ***49 possible types of solutions****.*
> *[Fasth, 2012]*

Results from paper 1 and paper 2 show a combination of the taxonomy and the matrix with discrete steps. The physical level 1-4 is defined as the task is performed by humans, i.e. the human is assembling (or performing) the task. Level 5-7 is defined as the machine assembling (or performing) the task. At the cognitive level, level 1-3 is the human who is monitoring the task while level 4-7 is the technique or machine that is monitoring the task.

5.2.3 THEORETICAL CONTRIBUTION FROM AN INDUSTRIAL PERSPECTIVE

This section will discuss the theoretical contribution with the results from the appended papers related to RQ3 in relation to the theoretical framework regarding assessment methods and assembly systems and based on quality of research i.e. from a validity perspective

(RA2: Validation of DYNAMO++ and the concept model)

The validity perspective can be divided into four different types: External validity, Construct validity, Internal validity, and Reliability (Yin, 2003). The DYNAMO++ methodology and the concept model could be quality-checked by discussing these four areas.

External validity means establishing a domain in which the study could be generalised. The externally validity has mostly been done in the assembly area context. External validity has been achieved through the thirteen case studies that have been conducted; according to Glaser and Strauss (Glaser and Strauss, 1967), it is the intimate connection with empirical reality that permits the development of a testable, relevant, and valid theory. Many researchers (Miles and Huberman, 1994, Strauss, 1987, Yin, 2003) agree that using multiple case studies could be one way to ensure quality and external validity. To reach further external validity the approach of triangulation has been used, described in Chapter 5.3.1. It is important to consider both qualitative and quantitative methods when performing a case study to broaden the perspective in terms of cause and effect and relation between different sets of parameters (Wacker, 1998).

Construct validity is accomplished by constructing correct measures for the concept that are being studied. Since the concept of Levels of Automation was the key point to measure and analyse, this is what has been measured. Frohm's taxonomy was used as an assessment method because it has been tested and validated in previous research projects and case studies (Granell, et al., 2007). Further it contains both cognitive and physical levels of automation which was the concept that should be tested. By using data and investigator triangulation, this increases the validity of the research (Yin, 2003).

Internal validity is achieved by establishing a causal relation. This was done by performing the thirteen case studies using triangulation of multiple investigators, within-case and cross-case analyses, and existing literature, which according to (Eisenhardt, 1989) are good tools in order to build theory based on case study research. Structured interviews and well documented measures were done in most of the cases, and this information was then used in order to do cross-case analyses. One tactic is to select categories or dimensions, and then to look for within-group similarities coupled with intergroup differences. Categories chosen in these cases were Levels of Automation, Triggers for Change and lean awareness. Results from six of the studies are presented in paper 3 (Fasth and Stahre, 2008).

Reliability is to ensure that the operation of the study could be repeated with the same results.
Two issues are important in reaching closure: when to stop adding cases, and when to stop iterating between theory and data. Ideally, researchers should stop adding cases when theoretical saturation is reached (Eisenhardt, 1989) (Theoretical saturation is simply the point at which incremental learning is minimal because the researchers are observing phenomena seen before,(Glaser and Strauss, 1967)). The final products of building theory from case studies may be concepts (e.g., the Mintzberg and Waters, 1982, deliberate and emergent strategies) or a conceptual framework (e.g., Harris & Sutton's, 1986, framework of bankruptcy). This is in line with results from paper 1, e.g. the development of the concept model developed from case studies and the DYNAMO++ methodology. Further, both novices and experienced users have been able to follow the methodology in a simple way, i.e. investigator triangulation, which increases the reliability.

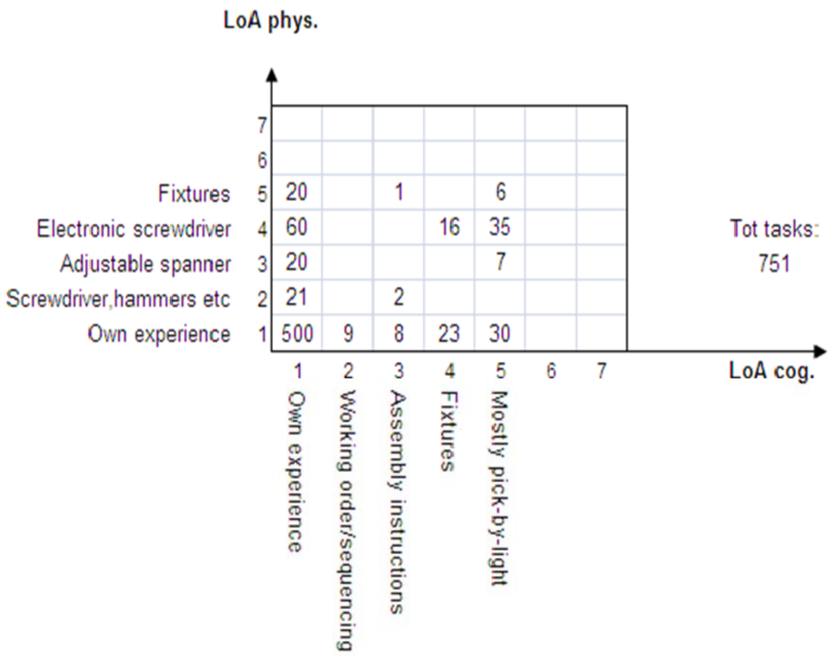
5.2.4 PRACTICAL CONTRIBUTION FROM AN INDUSTRIAL PERSPECTIVE

This section will discuss the practical contribution with the results in RQ1 in relation to the theoretical framework of Levels of Automation (LoA).

(RA3: Use of DYNAMO++ and the concept model.)

Results from the case studies show that the issue of Levels of Automation is often seen from a physical perspective, focusing on reducing cost as a primary parameter. Furthermore, results from the literature study of assessment methods, presented in paper 4, reveal that there is a lack of methods which consider both physical and cognitive automation as a prime parameter. By introducing the DYNAMO++ and the concept of LoA, i.e. to consider both the physical and cognitive LoA and to investigate other triggers for change, the companies' view broadens when it comes to solutions for redesigning the system.

The most illustrative and quantitative step in the method is the LoA-matrix. The matrix, illustrated in Figure 21, shows collected measures from ten case studies. Results from paper 1 [Fasth, 2008; Fasth, 2010; etc.] show that there is a need for a more detailed scale. If these tasks had been assessed with only three levels of physical automation (manual, semi-automatic, automatic), all tasks would have been classified as manual tasks. The more detailed scale with four (sometimes five) levels could be used in order to make finer improvements. In line with Porras and Robertsson (Porras and Robertsson, 1992), there is still a need for minor changes in a system. For example the physical LoA, level 1-4 could be used in order to determine and improve the (hand) tool that is used. This information could also be used in ergonomic studies. For the cognitive LoA, Levels 1-4 could tell the engineer what kind of support is used, for example whether it is working orders, sequencing (or kitting), pick-by-light etc.



CASE	No. Of Tasks
A	10
B	18
C	30
D	38
E	82
F	110
G	98
H	38
I	58
J	261
Total	751

FIGURE 21 OBSERVED TASKS FROM TEN CASE STUDIES, DOCUMENTED IN THE LOA MATRIX

The LoA-matrix is an easy-to-use tool for quantifying LoA in an illustrative way that could be used and understood from shop-floor level up to site manager level.

This section will discuss the practical contribution with the results from the appended papers related to RQ3 in relation to the theoretical framework related to Effects and Assembly systems.

(RA3: Shown effects of measuring and analyzing LoA)

Results from the appended papers have shown possible effects and consequences when considering LoA and three other relations (1, *Level of Competence (LoC), Level of Information (Lei) and Proactivity; 2, Time and Flexibility; and 3, Quality and Complexity)*. These will be discussed in the following section.

Competence (LoC), Information (LoI) and Proactivity

In order to create a possible proactive work setting, the ability in terms of competence and tools in terms of information system and automation solutions has to be available *to help the individual to take self-directed action, to anticipate or initiate change in the work system or work roles (Griffin, et al., 2007) and to handle frequent changes within the system (Dencker, 2011, Fasth, et al., 2010)*. Results from paper 5 show that it is a strong relation between the areas of automation, competence and information flow. Further, they show that all areas have to be considered in order to increase proactive behaviour among the operators. It is shown that if changing LoA the other areas will be affected; the challenge is to understand how much effort it takes for the operators and the system if changing LoA in terms of education, investments of soft- and hardware etc.

Time and Flexibility

More flexibility in manufacturing operations means more ability to adapt to customer needs, respond to competitive pressures, and be closer to the market (Slack, 2005). Results from papers 1 and 3 show that it is important to consider the production layout when examine possible solution. By combining different levels of automation, routing flexibility was created. Further, volume flexibility and cycle time were also affected in a positive way by the solutions.

Quality and Complexity

Earlier empirical results (Guimaraes, et al., 1999) show that in general, system complexity does affect performance negatively, and that training and the man/machine interface play important roles in minimizing the negative effect of system complexity on performance. Results from previous sections show that relations could be made between quality, complexity and cognitive automation. Beliefs are that cognitive automation can be used as a means to reduce the negative effects of choice complexity in terms of quality. Results from paper 6 show that it is possible to use quantitative measures in order to show relations between station complexity, quality and cognitive automation. These methods could be further used in order to improve both the resource efficiency and resource allocation in order to get an effective assembly system. Then, the operators' competence and experience should also be taken into consideration, which is not fully covered by using only these quantitative methods. The main conclusion is that there is evidence that cognitive support is needed in final assembly to minimize the negative effects of complexity.

5.3 EMPIRICAL AND THEORETICAL COLLECTION AND ANALYSIS

The following sections will discuss the results from the empirical and theoretical collection base on two perspectives i.e. the triangulation perspective and the validation perspective.

5.3.1 TRIANGULATION PERSPECTIVE

Within the triangulation perspective there are four areas of empirical collection that could be discussed according to (Dezin, 1970) and (Olsen, 2004). The use of these four perspectives will be discussed in the following section.

1. *Data triangulation*

Data triangulation means using a variety of data sources in a study. Both quantitative and qualitative data were collected within the case studies in order to achieve data triangulation, but also to get a more nuanced picture of the examined area, i.e. both "*numbers and words*" (Miles and Huberman, 1994). Furthermore, multiple case studies give a more generalised data collection. The results from the empirical collections were mostly used in papers 1, 2, 4 and 5. A drawback is that lab experiments have not been done to the extent that was wished for in order to collect even more data to strengthen some relations between LoA and other parameters in a more controlled way. This will be done in future work.

2. *Investigator triangulation*

The use of several different researchers or evaluators creates investigator triangulation but also reliability within the validation step of a methodology. Results in papers 4 and 5 are based on investigator triangulation though data gathering and the analysis were made in cooperation between three or more researchers. This method has not been used solely by industrial partners; the aim is that the method will be used by production engineers as a statistic and analytical tool for every-day follow-ups and for strategic investments.

3. *Theory triangulation*

- To use a multiple perspective to interpret a single set of data. Theory has been used from different domains in order to achieve theory triangulation. There are still other areas of interest that could be combined in order to make the concept model more logical, automated and generalised.

4. *Methodology triangulation*

- Using multiple methods to study a single problem or phenomenon. This is mainly done in papers 4 and 5 where three different methods in each paper are used in order to study the relation between Levels of automation and Proactivity in paper 4 and the relation between complexity, quality and Cognitive automation in paper 5. Furthermore, the use of both quantitative and qualitative methods also strengthens the methodology triangulation.

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5.4 FUTURE WORK

Results from the case studies conducted for this thesis show that more than 80 % of the tasks are performed based on the operators' own experience (see Figure 24, p.48). Some assumptions on why it looks like this could be: experienced operators that work on final assembly line at some case companies. The fact that some companies have u-cells with one product family and thereby decrease the variant complexity could be another explanation.

This manual level could affect other parameters in the system, such as time, quality etc. Results in paper 5 show a possible correlation between cognitive LoA, Quality and complexity. And as a part of a future study, the relation between different Levels of Automation and other parameters will be investigated in a more controlled environment, i.e. lab tests. This will be done in order to accomplish more statistically controlled experiments.

A second part of the future work will be to further develop the automated planning system regarding local resource allocation (Fasth, et al., 2012, Provost, et al., 2012) and automated generated work instruction due to different LoAs. Also it will investigate further the work done on algorithm developments (de Winter and Dodou, 2011) according to dynamically changeable function allocation with a human centred approach (not left-over function allocation) (Hoc, 2001). A related part will be to perform lab experiments regarding cognitive automation and different types of carrier and content to further develop and test these concepts (Fasth and Stahre, 2010, Fässberg, et al., 2012).

In order to make the DYNAMO++ and the concept model more generalised it would be interesting to apply the concept within other contexts such as manufacturing, health, mining etc.

6 CONCLUSION

This chapter contains conclusions related to the aim.

The aim of this thesis is:

By quantifying, measuring and analysing the physical and cognitive Levels of Automation, enable competitive assembly systems.

RQ 1: Why is it important to quantify Levels of Automation (LoA) in an assembly system context?

RQ 2: How should LoA be quantified, measured and analysed in assembly systems?

RQ 3: What are the expected effects of analysing and changing LoA?

Results presented in Paper 1 show that there is an ongoing debate, both in industry and academia on how to define physical automation, cognitive automation; and Levels of Automation. The debaters might not even be explicit that it is automation they are arguing about, especially when it comes to cognitive automation. Therefore, in order to reach the aim, definitions of physical automation, cognitive automation and Levels of Automation need to be clear and agreed upon as a first step. The author defines the terms as follows:

- **Physical automation** is defined as: "*technical solutions helping the operator to assembly the products e.g. WITH WHAT to assemble".*
- **Cognitive automation** is defined as: "*technical solutions helping the operator e.g. HOW to assemble (Levels 1-4) and situation control (Levels 5-7)".*
- **Levels of Automation** is defined as:" *the allocation of physical and cognitive tasks between resources (humans and technology), described as discrete steps from 1 (totally manual) to 7 (totally automatic), forming a 7 by 7 LoA matrix containing 49 possible types of solutions".*

With that definition of Levels of Automation, results from paper 1 show that it is possible to quantitatively measure automation based on seven ranking steps and also to visualise the result in the matrix. Further, companies could develop a company-specific "LoA-language" based on own examples within the matrix. This common language could be a help when discussing new LoA–investments. The LoA matrix with quantitative discrete steps could also be one way to illustrate the current state and be a base for discussion from operator level up to management level. Furthermore it is an easy way to compare different cells with each other, and could be used to find correlation with other parameters, i.e. quality, time, flexibility etc. Furthermore, results have shown possible effects and consequences when considering LoA and:

- Competence (LoC), Information (LoI) and Proactivity [Paper 5]
- Time and Flexibility *and* [Paper 1 and 3]
- Quality and Complexity [Paper 6]

The developed and validated methodology, DYNAMO++, and concept model [Paper 1,2, 3 and 4], gives the possibility to, in a structured way, analyse the current state and to find possible solution for the future that could be further analysed and specified in terms of simulation models etc. The concept model gives an understanding of the different areas that are important to consider in relation to LoA.

I therefore conclude that dynamically changeable automation and collaboration between highly-skilled humans and technology is the answer for competitive assembly systems.

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